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PARAMETRIC STUDY OF HELICOPTER AIRCRAFT SYSTEMS COSTS AND WEIGHTS

BY

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF ABBREVIATIONS

AAVSCOM	U.S. Army Aviation Systems Command
AC	Alternating Current
APU	Auxiliary Power Unit
C	Cost
CAC	Cumulative Average Cost
CER	Cost Estimating Relationship
DC	Direct Current
HP	Horsepower
IPS	Integrated Pneumatic System
MEW	Manufacturer's Empty Weight
NASA	National Aeronautics and Space Administration
OSD (PA&E)	Office of the Secretary of Defense (Planning, Analysis and Evaluation)
Q	Quantity
SAI	Science Applications, Inc.
W	Weight
WER	Weight Estimating Relationship
$FY--	Dollars for Fiscal Year --

PREFACE

This report presents the results of a study to determine weight estimating relationships and recurring production cost estimating relationships for helicopters at the system level. This study was sponsored by the National Aeronautics and Space Administration under contract number NAS2-8703. Mr. Joseph L. Anderson monitored the study for the V/STOL Systems Office of the V/STOL Aircraft Technology Division, Ames Research Center. Work was performed at two separate intervals, between February and October, 1977, and between December, 1978, and January, 1980, by the Economic Analysis Division of Science Applications, Inc. (SAI).

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EXECUTIVE SUMMARY

This report presents the results of a NASA-sponsored study to develop weight estimating relationships (WERs) and recurring production cost estimating relationships (CERs) for helicopters at the system level. The systems considered in this report correspond to the standard weight groups defined in Military Standard 1374A. They are:

Wing	Propulsion	Electrical
Rotor	Flight Controls	Avionics
Tail	Auxiliary Power	Furnishings and Equipment
Body	Instruments	Air Conditioning
Alighting Gear	Hydraulics	Anti-Icing
Nacelle	Pneumatics	Load and Handling

These systems make up a complete helicopter.

The WERs estimate system level weight based on performance or design characteristics which are available during concept formulation or the preliminary design phase.

The CER (or CERs in some cases) for each system utilize weight (either actual or estimated using the appropriate WER) and production quantity as the key parameters. The CERs provide a very useful tool for making preliminary estimates of the recurring production cost of a helicopter. Although the CERs are based on current technology, any systems which involve new designs and technologies* should be analyzed in greater detail using the CER based on current technology as a point of departure.

The weight estimating relationships were developed by performing various statistical analyses, including regressions on design and performance

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* It is unlikely that a helicopter which utilizes new technologies for every system will be designed or produced in the foreseeable future. Rather, future helicopters will probably be derivatives of current ones. Therefore, many of the CERs provided will be appropriate for estimating the costs of future helicopter designs.

characteristics and system (or subsystem) level weights for a wide variety of helicopters. Our data bank included over seventy helicopters, both military and commercial, with manufacturer's empty weights ranging from about 1,000 to over 30,000 pounds. After these data were adjusted to exclude more than one model of each helicopter type and, thereby, avoid biasing the WERs obtained, thirty different helicopters were represented.

The discussion provided for each system level WER notes alternative independent variables which were considered and provides coefficients of determination (r^2). Detailed weight data, design and performance data are also included.

Detailed cost data were available for only some helicopter systems. These data were regressed against corresponding weights to develop CERs. In order to develop cost estimating relationships for systems for which costs were not reported, novel methods and sources were used. One such source was helicopter industry subcontractors with extensive experience in supplying major components and subassemblies. They were contacted and interviewed. The general cost information which they provided on major components and subassemblies was then aggregated by system according to the proportion of total system weight. Also, cost data provided in our previous report (1)* for transport aircraft systems were used as a cross check or as a primary source where research indicated that this was appropriate.

Since the cost data varied substantially in terms of quality, confidence values were developed for each CER based on an evaluation of its data sources. Thus, anyone using the CERs has a basis for determining which ones he should be most confident of and which he might want to confirm or augment by using other data sources (such as company proprietary information) to which he might have access.

In summary, this report provides weight estimating relationships and cost estimating relationships for each helicopter system. Together, these

* Numbers in parentheses correspond to the document of the same number cited in the References.

enable recurring production costs to be estimated based on information available during concept formulation or the preliminary design phase. Because they are at the system level, selected WERs and CERs may be modified to reflect new designs or technologies and the sensitivity of total weight and cost to them may be evaluated.

In order to facilitate the use of the WERs and CERs, the number of independent variables included in them has deliberately been kept as small as would be consistent with reasonable accuracy.* At later stages of design, accuracy may be improved through the use of more complex, computer-based models such as those developed by helicopter manufacturers for in-house use.**

* Specifically, only twelve independent variables are included in the WERs, while the CERs are a function of only weight and quantity.

** For example, a set of WERs developed and used by one manufacturer included over 150 independent variables.

SECTION I
INTRODUCTION

A. OBJECTIVE

The objective of this report is to provide a rapid and easy means for estimating the recurring production cost of helicopters at the system level. In this report the system level refers to the eighteen major systems shown in Figure 1.1. These systems correspond to the standard weight groups defined in Military Standard 1374A. Several of these systems have been broken into subsystems so that their costs may be estimated with greater accuracy.

The recurring production cost estimating relationships (CERs) presented in this report should be useful to the NASA and to other government agencies, as well as to commercial and research firms for making estimates of the recurring production cost impact of alternative conceptual helicopter designs, technologies, materials and manufacturing methods during concept formulation and the preliminary design phase. Also, these estimates can be used by the NASA in screening and evaluating the user cost impact of potential aeronautical research and development programs which it might sponsor. Cost estimates made with this model should also be quite useful in developing initial design to cost (DTC) targets and in performing system design trade-off studies during preliminary design. These capabilities are made possible by the disaggregated nature of the CERs, which permits the user to modify them to reflect atypical designs.

The CERs estimate recurring production costs as a function of weight and production quantity. If known, actual weights may be used. If not, a set of corresponding system level weight estimating relationships (WERs) has been developed to estimate system level weight based upon performance or design characteristics available when the helicopter is in the early conceptual stages.

Figure 1.1

HELICOPTER SYSTEMS*

1. Wing
2. Rotor
3. Tail
   - A. Tail Rotor
   - B. Tail Structure
4. Body
5. Alighting Gear
6. Nacelle
7. Propulsion
   - A. Powerplant
   - B. Drive
   - C. Fuel
8. Flight Controls (Less Autopilot)
9. Auxiliary Power
10. Instruments
11. Hydraulics
12. Pneumatics
13. Electrical
14. Avionics (Including Autopilot)
15. Furnishings and Equipment
16. Air Conditioning
17. Anti-Icing
18. Load and Handling

Manufacturer's Empty Weight (MEW)

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* These systems correspond exactly to the standard weight groups defined in Military Standard 1374A, except that the Military Standard combines hydraulics and pneumatics into one standard weight group.

B. BACKGROUND

Early weight estimating relationships for aircraft assumed that subsequent or future aircraft would be much like their predecessors, possibly only larger or with more engines. These early relationships estimated in a gross way the manufactured weight of the aircraft less its engines. Many adjustments were required to make these simple relationships agree with the planned design of the new aircraft.

A similar situation existed with respect to cost estimating relationships. In the mid-1960s, the military became concerned with the cost of their weapon systems. As a result, their planners had to develop methods to estimate the costs of new systems. In 1964, the Planning Research Corporation published the first cost estimating relationships for military aircraft. The Rand Corporation has continued this to the present. The Rand Corporation has included RDT&E airframe, engines, and some weaponry in its cost estimating relationships. These relationships are based on past aircraft purchases and provide cost estimates at the total airframe level.

In assessing and prioritizing its aeronautical research programs, the NASA found that the Rand methods were not wholly satisfactory because it was necessary to make many detailed calculations and perform much analysis outside of the model to account for the incorporation of any new technologies.

Manufacturers have usually relied upon detailed industrial engineering estimates at the component level. To do this, the estimator specifies each engineering task, tool requirement and production operation based upon a set of detailed drawings. When ordinary operations and equipment will be required, standard cost factors are applied. If new techniques are to be used, cost factors must be developed. Industrial engineering estimates require an extraordinary amount of time and manpower and, because of this and their limited accuracy, they are not warranted for preliminary design purposes.

The NASA recognized the need to develop a cost model at the system level which would enable consideration of the costs of alternative designs with a fraction of the manpower required by the industrial engineering approach. Science Applications, Inc. (SAI) was given a contract to develop such a model. This effort was initially devoted to military and commercial transport aircraft. A model was developed which estimates the recurring production cost of existing transport aircraft within ten percent of their actual cost. This model is documented in NASA CR 151970, Parametric Study of Transport Aircraft Systems Cost and Weight.[1]

The NASA recognized the need for a similar capability to estimate the recurring production cost of helicopters at the system level. Since SAI was experienced in successfully developing such a methodology for transport aircraft and had developed an extensive cost data base for helicopters,[2] it was selected by the NASA to perform this study.

C. ORGANIZATION OF REPORT

The assumptions, analytical approach and methodology used in this study are discussed in Sections 2 and 3, for weight and cost respectively, and the complete sets of WERs and CERs developed are provided therein. The WERs and CERs developed for each system or subsystem are examined and discussed in detail in Sections 4 and 5.

SECTION 2

SUMMARY OF WEIGHT ANALYSIS AND METHODOLOGY

Weight and technical data were collected for over 70 military and commercial helicopter types and models. These data were screened to establish a representative group of 30 helicopters from which weight estimating relationships (WERs) were developed for the 18 systems presented in Figure 1.1. The objective of and methodology used to accomplish this part of the study are discussed below. Then, summary information and system level weight data are presented for the helicopters included in the data banks. Next, the WERs are presented in summary form. Finally, example applications of the WERs are provided. Relevant technical information and the specific data and methodology used in developing each WER are discussed in detail in Section 4.

A. OBJECTIVE AND METHODOLOGY

As noted earlier, the primary objective of this study was to develop rapid and easy means for estimating recurring production costs for helicopters at the system level. Cost has been found to correlate very well with weight. However, actual weights are obviously not available during the conceptual design phase. Therefore, reliable WERs for system level weights which would be compatible with the system and subsystem breakdown of the CERs were required.

Weight, performance and design data were collected for nearly 50 different helicopter models, comprising more than 70 types. The primary source for these data was information developed by AAVSCOM. However, these data were augmented with information from Jane's All the World's Aircraft, DMS Market Intelligence Reports, and manufacturers' weight statements, as appropriate.

Determination of Data Base and Validity of Data Points

From our initial data bank of 70 helicopters, some were deleted in order to create a more representative sample and to reduce bias. These adjustments were made for the following reasons:

- All experimental (paper) designs were eliminated from the sample (although prototypes were included) as it was felt they might not be representative of existing technologies or designs.

- Duplications of a basic helicopter model may cause regression bias in an equation. This is especially true for larger models. In such cases, the most "representative" model was included in the data base. For example, the data included the UH-1B, UH-1C, UH-1E, UH-1F, UH-1H and UH-1N, yet only the UH-1H was incorporated in our sample. (The UH-2B and -2D are an exception, since the weights of their systems are almost completely different and the MEW for the UH-2D is about 19 percent greater than that of the UH-2B). On the other hand, when two different types of the same helicopter model employed obviously different designs or technologies, both were included. For example, the UH-1N was used in addition to the UH-1H for the nacelle system, since they had different numbers of engines.

- Data may be missing or unreliable. For example, smaller nacelles usually had no defined surface area (due to their location in the fuselage). Therefore, they were not included in deriving the weight estimating relationship.

- Data points may be significantly above or below the general trend line for unknown reasons. Complex statistical procedures were applied to confirm suspect data points as "outliers" and to justify their exclusion. If the reason for an "outlier" eventually became known, it was included in the weight estimating relationship by use of a "dummy variable."

- Data for extraordinarily large helicopters often resulted in some unusually high correlations and/or sudden shifts in slope. For example, in the fuel system, the inclusion of data points for models with design gross weight greater than 100,000 pounds caused the coefficient of determination to increase from .77 to

.95, even though the effect on the slope was small. Typically, however, for most estimating relationships, system weights for large models cause significant changes in slope as well as in correlation. Weight estimating relationships which include large helicopters usually have large negative intercepts as well as steeper slopes, which might result in negative weight estimates for small models. Therefore, such data points were excluded from the sample.

The helicopter models which are included in our basic sample are listed in Table 2.1, together with information on the manufacturer, common name, primary user, mission, manufacturer's empty weight (MEW), design gross weight (W_g), and takeoff gross weight (TOGW). System level weights, which sum to MEW, are presented in Table 2.2.

For individual systems, the basic sample was augmented with other data as appropriate. When this was done, relevant information is included in the detailed weight analyses in Section 4.

Formulation of Weight Estimating Relationships

The system level weights were examined to determine their relationship with various design and/or performance characteristics which should be available early in the design phase. Twelve characteristics are used in the equations. They are listed in Table 2.3, together with the approximate percentage of manufacturer's empty weight which they estimate. Four of these characteristics estimate about 88 percent of MEW. As shown, design gross weight is a key variable. It is equal to manufacturer's planned empty weight plus useful load. It correlates very well with takeoff gross weight (differences can be explained as planned vs. actual). However, design gross weight was used instead of takeoff gross weight because it is established during the preliminary design phase.

WERs were developed by determining the relationship between weight and one or more design or performance characteristics. The WERs provided are typically characterized by a slope and an intercept which have been statis-

Table 2.1

SUMMARY OF HELICOPTER WEIGHT DATA BASE

HELICOPTER MODEL	MANUFAC-TURER	COMMON NAME	MISSION	PRIMARY USER	MEW	W_g	TOGW
269A	Hughes				985	1,600	1,582
OH-6A	Hughes	Cayuse	Light observation helicopter	U.S. Army	1,202	2,400	2,400
TH-57A	Bell	Kiowa-Sea Ranger	Observation,recon-naissance,fire sup-port,utility,training	U.S. Navy	1,535	2,900	2,555
OH-58A	Bell	Kiowa	Light observation helicopter	U.S. Army	1,545	3,000	3,000
OH-23G	Hiller				1,905	2,800	2,620
OH-13S	Bell		Scout helicopter	U.S. Army	1,926	2,850	2,850
BO105	Vertol	Executive	Executive transport	Commercial	2,342	4,630	4,569
286	Lockheed				2,981	4,700	4,700
UH-1H	Bell	Iroquois	General purpose, Assault/transport	U.S. Army U.S. Air Force	5,235	6,600	6,654
H-52A	Sikorsky		Prototype—never produced		5,585	7,500	8,308
UH-19D	Sikorsky		Troop movement/ medical evacuation	U.S. Army U.S. Air Force	5,831	7,100	7,200
UH-2B	Kaman	Seasprite		U.S. Navy	5,909	7,378	8,362

Table 2.1 (Continued)

SUMMARY OF HELICOPTER WEIGHT DATA BASE

HELICOPTER MODEL	MANUFAC-TURER	COMMON NAME	MISSION	PRIMARY USER	MEW	W_g	TOGW
AH-16C	Bell				6,913	10,000	N/A
UH-2D	Kaman	Seasprite	Utility helicopter	U.S. Navy	7,633	10,187	N/A
YAH-64	Hughes		Advanced attack helicopter (AAH)	U.S. Army	7,848	13,950	13,200
CH-34A	Sikorsky		Anti-submarine warfare (ASW)(Marines), general purpose(Army)	U.S. Marine Corps, U.S. Army	7,803	11,867	12,797
CH-21C	Vertol		Transport	U.S. Air Force	9,158	13,300	13,301
YUH-63	Bell		AAH	U.S. Army	9,729	15,645	14,954
YUH-61A	Vertol		Utility tactical transport aircraft system (UTTAS)	U.S. Army	9,826	15,313	15,105
YUH-60A	Sikorsky		UTTAS	U.S. Army	10,222	16,250	15,850
SH-3A	Sikorsky	Sea King	ASW	U.S. Navy	11,459	18,064	18,060
S-67	Sikorsky	Blackhawk	High speed attack helicopter	Private-venture	11,752	17,300	19,589
AH-56A	Lockheed				12,077	18,300	18,265
CH-46F	Vertol	Sea Knight	Cargo transport	U.S. Navy, U.S. Marine Corps	13,313	20,800	20,284

Table 2.1 (Continued)

SUMMARY OF HELICOPTER WEIGHT DATA BASE

HELICOPTER MODEL	MANUFAC-TURER	COMMON NAME	MISSION	PRIMARY USER	MEW	W_g	TOGW
CH-47A	Vertol	Chinook	All-weather,medium transport	U.S. Army	17,752	33,000	33,001
CH-54A	Sikorsky	Tarhe	Heavy lift	U.S. Army	19,192	38,000	38,733
CH-37A	Sikorsky				21,238	30,342	31,000
YH-16A	Vertol		Prototype--never produced		22,655	34,000	34,001
CH-53A	Sikorsky	Sea Stallion		U.S. Navy	23,097	33,500	35,728
347	Vertol		Prototype--never produced		24,797	42,500	42,500

Table 2.2

HELICOPTER SYSTEM WEIGHT SUMMARY

MODEL	WING W_1	ROTOR W_2	BLADE ASSEMBLY W_{2A}	HUB & HINGE W_{2B}	TAIL W_3	ROTOR W_{3A}	STRUCTURE W_{3B}
269A		(115)	66	49	(9)	5	4
OH-6A		(174)	109	65	(23)	7	16
TH-57A		(277)	187	90	(34)	8	26
OH-58A		(281)	190	91	(32)	10	22
OH-23G		(311)	163	148	(21)	17	4
OH-13S		(284)	182	102	(17)	8	9
BO105		(462)	264	198	(56)	22	34
286		(726)	427	299	(69)	29	40
UH-1H		(742)	406	336	(84)	30	54
H-52A		(785)	425	360	(106)	53	53
UH-19D		(786)	422	364	(101)	60	41
UH-2B		(1,329)	720	609	(96)	68	28
AH-16C	240	(1,400)	675	725	(151)	73	78
UH-2D		(1,325)	720	605	(216)	104	112
YAH-64	252	(1,207)	664	543	(237)	85	152
CH-34A		(1,313)	652	661	(260)	74	186
CH-21C		(1,344)	678	666	(162)		162
YUH-63	349	(1,656)	979	677	(184)	84	100
YUH-61A		(1,645)	1,052	593	(344)	76	268
YUH-60A		(1,705)	809	896	(346)	105	241
SH-3A		(2,328)†	1,012	1,316	(222)	99	123
S-67	453	(2,348)	1,039	1,309	(468)	103	365
AH-56A	539	(2,812)*	1,239	1,133	(287)	130	157
CH-46F		(2,424)†	918	1,506			
CH-47A		(2,996)	1,610	1,386			
CH-54A		(4,052)	2,115	1,937	(519)	360	159
CH-37A	621	(3,251)	1,749	1,502	(570)	345	225
YH-16A		(4,536)	2,198	2,338	(133)		133
CH-53A		(4,489)†	2,120	2,369	(673)	367	306
347		(5,054)	2,740	2,314			
TOTAL	2,454	(52,157)*	26,530	25,187	(5,420)	2,322	3,098
%MEW	0.9	(18.4)*	9.4	8.9	(1.9)	0.8	1.1

* Includes propeller - 440 pounds.

† Includes blade folding apparatus.

Table 2.2 (Continued)

HELICOPTER SYSTEM WEIGHT SUMMARY

MODEL	BODY W_4	ALIGHTING GEAR W_5	NACELLE W_6	PROPULSN W_7	POWER-PLANT W_{7A}	DRIVE W_{7B}	FUEL W_{7C}
269A	125	53	7	(503)	336	142	25
OH-6A	242	70	8	(341)	192	113	36
TH-57A	335	45	32	(396)	194	176	26
OH-58A	332	35	36	(419)	165	215	39
OH-23G	248	88	79	(771)	551	198	22
OH-13S	221	54	37	(845)	588	155	102
BO105	472	94	25	(804)	348	395	61
286	496	142	12	(865)	369	440	56
UH-1H	1,035	121	114	(1,632)	683	658	291
H-52A	1,263	485	63	(1,115)	360	621	134
UH-19D	985	287	147	(2,525)	1,244	1,064	217
UH-2B	1,259	343	161	(1,467)	635	733	99
AH-16C	1,327	134	180	(1,912)	835	825	252
UH-2D	1,394	424	371	(2,365)	805	1,361	199
YAH-64	1,311	396	123	(2,687)	1,089	1,101	497
CH-34A	1,044	475	150	(3,189)	1,737	1,091	361
CH-21C	1,884	522	89	(3,371)	1,809	1,393	169
YUH-63	1,726	497	252	(3,020)	1,093	1,523	404
YUH-61A	1,648	500	210	(2,767)	831	1,576	360
YUH-60A	1,729	659	155	(2,730)	862	1,405	463
SH-3A	2,009	748	131	(2,724)	701	1,763	260
S-67	1,695	656	156	(3,466)	941	2,123	402
AH-56A	1,872	653	231	(2,895)	969	1,680	246
CH-46F	3,126	591	71	(3,235)	951	2,010	274
CH-47A	4,487	1,086	176	(5,151)	1,342	3,531	278
CH-54A	2,685	1,794	66	(6,857)	2,185	3,797	875
CH-37A	3,247	983	1,098	(8,419)	5,516	2,567	336
YH-16A	5,424	1,244	119	(7,822)	3,706	3,679	437
CH-53A	5,260	1,019	394	(6,057)	1,762	3,919	376
347	6,259	1,114	191	(6,881)	1,741	3,796	1,344
TOTAL	55,140	15,312	4,884	(87,231)	34,540	44,050	8,641
%MEW	19.5	5.4	1.7	(30.7)	12.2	15.5	3.0

Table 2.2 (Continued)

HELICOPTER SYSTEM WEIGHT SUMMARY

MODEL	FLIGHT CONTROLS W_8	AUXILIARY POWER PLANT W_9	INSTRU- MENTS W_{10}	HYDRAULIC W_{11}	PNEUMATIC W_{12}	ELEC- TRICAL W_{13}	AVIONICS W_{14}
269A	51		8			59	[illegible]
OH-6A	65		30			68	[illegible]
TH-57A	133		29			110	[illegible]
OH-58A	125		27			85	[illegible]
OH-23G	108		34			111	96
OH-13S	155		24			130	91
BO105	189		25			168	
286	327		58	38		130	20
UH-1H	357		59	33		360	246
H-52A	353		124	43		419	427
UH-19D	164		70	47		327	110
UH-2B	301		142	42		233	318
AH-16C	469		101	110		400	283
UH-2D	300		166	52		293	362
YAH-64	419	135	99	96		294	303
CH-34A	378		108	26		327	269
CH-21C	561		134	62		342	247
YUH-63	596	137	127	162		[illegible]	308
YUH-61A	721	193	153			389	456
YUH-60A	694	194	152	87		464	466
SH-3A	654		368	46		391	1,273
S-67	780		187	40		397	737
AH-56A	1,021	136	127	86		377	[illegible]
CH-46F	828	106	158	168		654	[illegible]
CH-47A	1,212	99	172	212		555	303
CH-54A	1,161	183	284	168		472	435
CH-37A	965		191	129		497	269
YH-16A	1,239		176	224		708	303
CH-53A	1,168	211	395	132		601	[illegible]
347	1,921	177	195	176		617	371
TOTAL	17,413	1,571	3,923	2,179		10,387	[illegible]
%MEW	6.1	0.6	1.4	0.8		3.7	[illegible]

Table 2.2 (Continued)

HELICOPTER SYSTEM WEIGHT SUMMARY

MODEL	FURNISH & EQUIP W_{15}	AIR CONDIT W_{16}	ANTI-ICING W_{17}	LOAD & HANDLING W_{18}	TOTAL MEW
269A	33	11			985
OH-6A	58	9	1		1,202
TH-57A	64	27			1,535
OH-58A	42	25			1,545
OH-23G	32	4			1,905
OH-13S	30	40			1,926
BO105	47				2,342
286	84	14			2,981
UH-1H	408	44			5,235
H-52A	216	88	9	89	5,585
UH-19D	205	77			5,831
UH-2B	131	25	56	6	5,909
AH-16C	130	76			6,913
UH-2D	166	35	33	131	7,633
YAH-64	185	99	5		7,848
CH-34A	189	72		3	7,803
CH-21C	258	137		45	9,158
YUH-63	202	98	6		9,729
YUH-61A	650	78	33	39	9,826
YUH-60A	675	58	28	60	10,222
SH-3A	400	86	23	56	11,459
S-67	230	126		13	11,752
AH-56A	274	75	42		12,077
CH-46F	854	127	130	196	13,313
CH-47A	866	145	34	258	17,752
CH-54A	218	94	20	184	19,192
CH-37A	810	176		12	21,238
YH-16A	425	165		137	22,655
CH-53A	1,289	234	77	439	23,097
347	1,337	155	47	302	24,797
TOTAL	10,508	2,400	544	1,990	283,445
%MEW	3.7	0.8	0.2	0.7	100.0

Table 2.3

DESIGN AND PERFORMANCE CHARACTERISTICS
USED IN WERs

DESIGN OR PERFORMANCE CHARACTERISTIC	PERCENT OF MEW
Design Gross Weight	29.1
Body Surface Area	26.4
Blade Planform Surface Area	18.4
Engine Horsepower	13.6
Fuel Quantity	3.0
Number of Passengers and Crew	2.2
Vehicle Sink Speed	1.8
Range	1.8
Nacelle Surface Area	1.7
Tail Surface Area	1.1
Constant for Auxiliary Power Plant (if installed)	0.5
Wing Surface Area	0.4
	100.0

tically determined to represent most effectively the data from which they were derived. The basic formulae for deriving the slope and intercept for a simple regression are:

- Slope: $b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma X^2 - (\Sigma X)^2}$
- Intercept: $a = \Sigma Y - b\Sigma X.$

These results can be directly derived from the raw data. The formulae for multiple regression are more complex and are not presented here, but may be found in Wonnacott and Wonnacott, Introductory Statistics, Chapter 13.

Most systems or subsystems were found to be explained adequately with only one variable; the rest required two. After examining several alternative explanatory variables, those which combined the best functional and statistical qualities were included in the weight estimating model. Variables which had intuitive appeal but had less explanatory power are discussed in the detailed weight analyses of each system.

After determining the relevance of selected design and performance characteristics to system or subsystem weight, analyses were performed to determine:

- The degree to which some characteristics of the helicopter are related to weight and design and performance characteristics;
- Linearity or non-linearity;
- Reliability as measured by various statistical tests.

Configuration differences include both single vs. tandem rotor helicopters and cargo vs. non-cargo models, for which separate equations might be appropriate.

Differences within each characteristic were investigated for statistical significance. For example, tests of significance were performed on the influence of tandem configurations on tail structure weight. It was found that tail structure on tandem helicopters were on the average 111 pounds lighter than trend line estimates derived on the basis of single helicopters. The slope of the tandem models can be hypothesized to be the same, although the intercept is clearly different. Therefore, an adjustment (dummy variable) of -111 pounds was incorporated into the equation for tandem models.

Different configurations can also affect the slope of the WER, thereby requiring separate equations for each configuration. For example, the coefficients of the various avionics equations are significantly different, reflecting different mission requirements.

Data were carefully scrutinized to determine whether they indicated linear or non-linear relationship. When the plotted data revealed any significant non-linear trend, logarithmic transformations were determined. Only two systems were found to have any significantly non-linear trends. The non-linear trend line for the tail rotor fits the data points better than its linear counterpart throughout the relevant range. A weaker but recognizable logarithmic trend also appears in the electrical system weight. Linear equations were also derived for comparison.

The application of logarithmic or exponential transformations should be used carefully. Such transformations reduce the relative values of data points at the higher ranges and increase the relative importance of data points near the origin on the graph. Only when a linear representation is clearly inferior should a logarithmic equation be derived.*

A common abuse of non-linear transformations is to achieve a (marginally) higher correlation when no intuitive reason for its use exists. For example, the fuel subsystem's linear equation produces a correlation lower than other equations, increasing the temptation to explore non-linear possibilities. The variance from the trend line clearly increases with the size of the fuel tanks. A redistribution of the relative weights through logarithmic transformation reduces the relative variance of the larger tanks, resulting in a slightly higher correlation, but the function is essentially linear.

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* A logarithmic equation refers to the transformation of the data itself: $\ell y = 2 + b\ \ell x$. This is distinct from a linear equation plotted on double log graph paper, which is also linear in appearance.

Tests of Significance

After determining how helicopters of various configuration related to the assembled weight, design and performance data, and whether the weight estimating relationship was linear or non-linear in form, various statistical tests of significance were performed to assure the reliability of the WERs. These include: the "t" test, coefficient of determination and tests of co-variance. They are discussed below.

"T" Test

The "t" test is a means of determining whether separate equations should be used based on differing design or performance characteristics.* The greater the differences between the slopes and intercepts of the equations, the greater is the probability that the characteristics "explain" the differences.

The derived values for "t" can be compared with numerous benchmark statistics based on tables of significance which are available in most statistical manuals, e.g., in Wonnacott and Wonnacott, Introductory Statistics.

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* Intercepts:

$$t = \frac{a - \alpha}{s\sqrt{\frac{\Sigma X^2}{n\Sigma x^2}}}$$

where, a = actual intercept for "standard" data points, excluding points with differing characteristics

α = intercept for remaining data points, assuming same slope

$\Sigma y^2 = \Sigma Y^2 - (\Sigma Y)^2/n$

$\Sigma x^2 = \Sigma X^2 - (\Sigma X)^2/n$

$\Sigma e^2 = \Sigma y^2 - b^2\Sigma x^2$

$s^2 = \Sigma e^2/(n-2)$

$s = \sqrt{\Sigma e^2/(n-2)}$

Slopes:

$$t = \frac{b - \beta}{s/\sqrt{\Sigma x^2}}$$

where, b = slope for data points not possessing differing characteristic

β = slope for data points possessing characteristic

s and Σx^2 as before

For quick reference, the resulting "t" statistic should be at least 2. This is a "rule of thumb" measure of significance at a 95 percent level of confidence. If the result is clearly less than 2, the above tests of significance simply show that any difference in intercepts (a and α) or slope (b and β) of a standard linear equation based on differing configurations are due to the random nature of the data points around the trend line rather than to the different configurations themselves.

It should be noted that most differences due to configuration should be obvious by inspection when plotted on a graph and that formal tests are generally not needed, unless significant doubt arises.

<u>Coefficient of Determination</u>

The most comprehensive measure of association between two or more variables is the coefficient of determination (r^2), which is referred to as the "correlation" between variables. It is the degree to which variations in the dependent variable, y (weight), can be explained by variations in the explanatory variable(s), x's (design and/or performance characteristics). Equivalently, it can be expressed as:

$$\frac{\text{explained variations in y}}{\text{total variations in y}} = 1 - \frac{\text{unexplained variations in y}}{\text{total variations in y}} .$$

From the above equations, it can easily be inferred that the r^2 must fall between zero and one. The closer the data points are to the trend line, the smaller the unexplained variation and the higher the r^2.*

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* The coefficient of correlation, r, is the square root of the coefficient of determination and takes the sign of the slope of the trend line. For all values between zero and one, the coefficient of correlation leads to a more optimistic measure of the power of the explanatory variable, which is higher than the ratio of the explained to the total variation. The r^2 is therefore a more conservative statistic and relates more directly to the measure of reliability.

Many formulae exist for the computation of r^2, but the most practical is

$$\left(\frac{n\Sigma XY - \Sigma X\Sigma Y}{\sqrt{[n\Sigma X^2 - (\Sigma X)^2][n\Sigma Y^2 - (\Sigma Y)^2]}}\right)^2$$

which can be computed directly from the raw data.

(continued)

Tests of Covariance

To the extent that additional independent variables reduce the unexplained variation in the dependent variable, the r^2 will improve, but this depends on the correlation between the two explanatory variables (covariance). The higher the correlation between them ($r^2_{x_1x_2}$), the less likely that the multiple correlation coefficient $r^2_{x_1x_2 \cdot y}$ will be significantly larger than $r^2_{x_1y}$ or $r^2_{x_2y}$. For example, the weight estimating relationship for the instrument system yielded an r^2 of .7507 with horsepower, of .7313 with design gross weight, and of .7253 with fuel capacity. Inclusion of two or more variables raised the r^2 to only .7895. Covariance (r^2) was very high, e.g., .9266 between horsepower and fuel capacity, and .8405 beween horsepower and design gross weight.

Many covariance figures for the variables considered in deriving the weight estimating relationships were too high (typically .8 or more) to allow for multiple regression. On the other hand, some independent variables yielded a simple correlation coefficient so high (e.g., blade planform surface area in the main rotor equation) that the inclusion of other variables would not have improved the fit.

Related to the problem of high correlation between estimators is the "dominance" of one estimator over another in a multiple regression equation. For example, the following WER was obtained for instruments: $W_{10} = 48.279 + .0278HP_e - .0102G$. The positive coefficient for horsepower (HP_e) is, in fact, close to that derived for the simple, single variable equation (.0267),

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The same principle applies to multiple regression equations of the type

$$y = a + b_1X_1 + b_2X_2 + \ldots + b_nX_n.$$

The general expression for the multiple correlation coefficient for two independent variables, X_1 and X_2, is

$$r^2_{x_1x_2 \cdot y} = \frac{r^2_{x_1y} + r^2_{x_2y} - 2r_{x_1y}r_{x_2y}r_{x_1x_2}}{1 - r^2_{x_1x_2}}$$

Expressions for equations with three or more independent variables become more complex and are not presented here; their computation normally requires a computer. Fortunately, none of the weight estimating relationships derived in this study has more than two estimators.

but the fuel quantity coefficient is both negative and statistically insignificant, which is illogical. (The coefficient for a simple regression is actually +.181). The result arises from the superior r^2 of the weight with respect to the horsepower (HP_e) (.7893) to that of the fuel quantity (G) (.7253) and the high covariance (.9266) between the two estimators (HP_e and G). This is confirmed by the multiple correlation coefficient (.7895) which is practically identical to that of the horsepower alone. Statistically speaking, the horsepower estimator is clearly "robust" and can stand alone, while the fuel quantity estimator adds practically nothing.

It is also possible that neither estimator completely dominates the other. For example, another multiple regression was derived for instruments: $W_{10} = 44.117 + .0159HP_e + .00224W_g$. Compared with the simple r^2 with HP_e (.7507), the r^2 for W_g alone is fairly close: .7313. Furthermore, covariance between HP_e and W_g is lower than in the previous case (.8405). As the separate coefficients for HP_e and W_g for simple regressions are +.0267 and +.00503 respectively, the inclusion of both explanatory variables into the above multiple regression "weakens" their coefficients. However, they remain positive. The multiple correlation coefficient is .7739 for this equation, which is only slightly above that for HP_e alone.

In summary, weight estimating relationships using only one or two variables have been derived for all systems and subsystems considered. These WERs have very high correlations and have passed rigorous statistical tests of significance, in order to assure their validity and reliability. Equations representing more than 85 percent of their MEW yield r^2s of more than .90 and only 9 percent of the MEW have r^2s of less than .80. Due to their linear strength and tendency towards covariance, most of the relationships are linear and simple.

B. SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

The system level weight estimating relationships which have been derived in accordance with the methodology discussed above are summarized in Table 2.4, together with the r^2 calculated for each, the approximate

Table 2.4

SUMMARY OF HELICOPTER SYSTEM
WEIGHT ESTIMATING RELATIONSHIPS

System	Equation	r^2	%MEW	Notes
1. Wing	$W_1 = -49.967 + .970S_w + .0212W_g$	0.9385	< 1	
2. Rotor (Main)				
Blades	$W_{2A} = -88.742 + 6.403S_{pl}$	0.9713	17	
Hub & Hinge	$W_{2B} = -105.943 + 5.761S_{pl}$	0.9626		
Total	$W_2 = -194.685 + 12.164S_{pl}$	0.9774		
3. Tail				
Rotor	$\ln W_{3A} = -8.327 + 1.352 \ln W_g$	0.9497	1	
	$W_{3A} = -29.916 + .0102W_g$	0.9180		Alt.
Structure	$W_{3B} = -17.872 + 2.829S_{tt} + K_t$	0.9178		
4. Body	$W_4 = -269.023 + 2.356S_b$	0.9684	21	
5. Alighting Gear	$W_5 = 161.361 + .0117W_g - 17.480V_{ss}$	0.8061		Skid
	$W_5 = 85.875 + .0304W_g$	0.9218		Wheeled
	$W_5 = -5.489 + .0342W_g$	0.9347	5	All
6. Nacelle	$W_6 = -64.779 + 2.401S_n$	0.9050	1	
7. Propulsion				
Powerplant*	$W_{7A} = 304.483 + 1.027HP_e$	0.9549	31	Recip., 1 eng.
	$W_{7A} = 211.546 + .229HP_e$	0.9817		Recip., 2 eng.
	$W_{7A} = 130.243 + .369HP_e$	0.8263		Turbo., 1 eng.
	$W_{7A} = 408.198 + .192HP_e$	0.9176		Turbo., 2 eng.
Drive System	$W_{7B} = -35.551 + .101W_g$	0.9657		
Fuel Tanks	$W_{7C} = 10.974 + .790G$	0.7732		
8. Flight Controls	$W_8 = 62.025 + .0334W_g$	0.9475	6	

* Includes: Engine, air induction, exhaust and cooling, engine controls and start system.

Table 2.4 (Continued)

SUMMARY OF HELICOPTER SYSTEM
WEIGHT ESTIMATING RELATIONSHIPS

System	Equation	r^2	%MEW	Notes
9. Auxiliary Power	$W_9 = 157$	—	< 1	Constant
10. Instruments	$W_{10} = 50.507 + .0267HP_e$	0.7507	2	
11. Hydraulics	$W_{11} = 15.890 + .00446W_g$	0.6574	< 1	
12. Pneumatics	———	—	0	
13. Electrical	$\ell n\ W_{13} = .903 + .733\ \ell n\ S_b$	0.8547	4	
	$W_{13} = 139.947 + .234S_b$	0.8160		Alt.
14. Avionics	$W_{14} = 301.770 + .0231W_g - .687R$	0.8923	3	USN Trans &
	$W_{14} = -20.814 + .00739W_g + .585R$	0.9177		USA Trans i
	$W_{14} = -59.041 + .0175W_g + .348R$	0.9761		Other
15. Furnishings and Equipment	$W_{15} = -8.106 + .176S_b + 20.456(N_p+N_c)$	0.9034	4	
16. Air Conditioning	$W_{16+17} = 28.844 + .0730S_b$	0.8172	1	
17. Anti-Icing			< 1	
18. Load and Handling	$W_{18} = -71.875 + .111S_b + 3.489(N_p+N_c)$	0.7704	< 1	

Table 2.4 (Continued)

SYMBOLS USED IN WERs

D_v	Dive velocity (mi/hr)
G	Number of gallons
GBR	Gear box ratio
HP_e	Engine horsepower
K_t	Tandem constant for tail structure
LOLEO	Oleo length (in)
N_c	Number of crew
N_p	Number of passengers
OLTRV	Oleo travel (in)
R	Range (mi)
RPM	Engine RPM
S_b	Body surface area (ft^2)
S_n	Nacelle surface area (ft^2)
S_{pl}	Blade planform surface area (ft^2)
S_{tt}	Total tail surface area (ft^2)
S_w	Wing surface area (ft^2)
TRR	Tail rotor radius (ft)
V_{ss}	Vehicle sink speed (ft/sec)
W_g	Design gross weight (lb)

percentage of manufacturer's empty weight they represent and notes related to their limitations or use. The WERs included in Table 2.4 are the preferred relationships which were derived. They are discussed in detail in Section 4, together with alternative WERs which were also derived. The alternative WERs may be more appropriate for special cases where, for example, the characteristic(s) upon which the preferred WERs are based may be inapplicable.

C. EXAMPLE APPLICATIONS OF WEIGHT ESTIMATING RELATIONSHIPS

The WERs were applied to those helicopter models chosen to represent a range of design gross weights. They are: Bell UH-1H, 6,600 lbs.; Bell UHX-43, 9,500 lbs.; and Boeing CH-47A, 33,000 lbs. (The data base comprises helicopter models ranging from 1,600 to 42,500 lbs. in design gross weight).

Because of the breadth of the data base (70 commercial and military helicopter models and types), reliable design, performance and weight data for other helicopters were generally unavailable. Therefore, two of the models selected to test the WERs were taken from the data base. However, the Bell experimental model (UHX-43) was not in the data base but had sufficient data and performance criteria for the purpose and so it was chosen to be tested.

Estimates were fairly close to the actual total weights for each model tested. Large percentage variances sometimes occurred in small systems and errors as large as 80 percent were observed. These were due entirely to the low correlations of those WERs (.63 - .80). Because the larger systems (i.e., rotor, propulsion, body, etc.) had strong correlations, variances between estimated and actual weights were small for them and tended to offset each other.

In general, WERs for the helicopter models tested yielded estimates within about 5 percent of the overall MEW, which implies strong correlations at standard confidence levels.

The variables used in the calculations and the results for these three helicopters are shown in Tables 2.5, 2.6, and 2.7.

Table 2.5

UH-1H WEIGHT ESTIMATE

Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing				
2. Rotor(s)	$S_{pl} = 76.9$	741	742	- 0.3
3. Tail		(106)	(84)	(+ 26.2)
Rotor	$W_g = 6,600$	35	30	+ 16.7
Structure	$S_{tt} = 31.3$	71	54	+ 31.5
4. Body	$S_b = 626$	1,206	1,035	+ 16.5
5. Alighting Gear	$W_g = 6,600$ $V_{ss} = 6.00$	134	121	+ 10.7
6. Nacelle	$S_n = 82.7$	134	114	+ 17.5
7. Propulsion		(1,332)	(1,632)	(- 18.4)
Powerplant	$HP_e = 1,103$	523	683	- 23.4
Drive System	$W_g = 6,600$	631	658	- 4.1
Fuel System	$G = 211$	178	291	- 38.8
8. Flight Controls	$W_g = 6,600$	282	357	- 21.0
9. Auxiliary Power				
10. Instruments	$HP_e = 1,103$	80	59	+ 35.6
11. Hydraulics	$W_g = 6,600$	45	33	+ 36.4
12. Pneumatics				
13. Electrical	$S_b = 626$	286	360	+ 20.6
14. Avionics	$W_g = 6,600$ $R = 318$	214	246	- 13.0
15. Furnishings and Equipment	$S_b = 626$ $N_p + N_c = 13$	368	408	- 9.8
16. Air Conditioning 17. Anti-Icing	$S_b = 626$	74	44	+ 68.2
18. Load and Handling				
TOTAL		5,002	5,235	- 4.4

Table 2.6

UHX-43 WEIGHT ESTIMATE

Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing				
2. Rotor(s)	S_{pl} = 97.4	990	927	+ 6.8
3. Tail		(129)	(101)	(+ 27.7)
Rotor	W_g = 9,500	58	46	+ 26.1
Structure	S_{tt} = 31.5	71	55	+ 29.1
4. Body	S_b = 493	893	1,032	- 13.5
5. Alighting Gear	V_{ss} = 8 W_g = 9,500	133	119	+ 11.8
6. Nacelle	S_n = 80	127	127	-0-
7. Propulsion		(1,941)	(1,779)	(+ 9.1)
Powerplant	HP_e = 2,050	886	853	+ 3.9
Drive System	W_g = 9,500	924	794	+ 16.4
Fuel Tanks		131*	131	
8. Flight Controls	W_g = 9,500	379	411	- 7.8
9. Auxiliary Power				
10. Instruments	HP_e = 2,050	105	61	+ 72.1
11. Hydraulics	W_g = 9,500	58	70	- 17.1
12. Pneumatics				
13. Electrical	S_b = 493	232	411	- 43.6
14. Avionics	W_g = 9,500 R = 300	225	227	- 0.9
15. Furnishings and Equipment	S_b = 493 $N_p + N_c$ = 15	386	383	+ 0.8
16. Air Conditioning } 17. Anti-Icing }	S_b = 493	65	50	+ 30.0
18. Load and Handling				
TOTAL		5,663	5,697	- 0.6

* Actual fuel tank weight. No fuel capacity statistic available.

Table 2.7

CH-47A WEIGHT ESTIMATE

Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing				
2. Rotor(s)	S_{pl} = 136.5	2,932	2,996	- 2.1
3. Tail				
Rotor				
Structure				
4. Body	S_b = 2,150	4,796	4,487	+ 6.9
5. Alighting Gear	W_g = 33,000	1,089	1,086	+ 0.3
6. Nacelle	S_n = 108	195	176	+ 10.8
7. Propulsion		(5,052)	(5,151)	(- 1.9)
Powerplant	HP_e = 4,400	1,253	1,342	- 6.6
Drive System	W_g = 33,000	3,298	3,531	- 6.6
Fuel Tanks	G = 620	501	278	+ 80.2
8. Flight Controls	W_g = 33,000	1,164	1,212	- 4.0
9. Auxiliary Power		157	99	+ 58.6
10. Instruments	HP_e = 4,400	168	172	- 2.3
11. Hydraulics	W_g = 33,000	163	212	- 23.1
12. Pneumatics				
13. Electrical	S_b = 2,150	643	555	+ 15.9
14. Avionics	W_g = 33,000 R = 225	355	303	+ 17.1
15. Furnishings and Equipment	S_b= 2,150 $N_p + N_c$ = 35	1,086	866	+ 25.4
16. Air Conditioning 17. Anti-Icing	S_b = 2,150	186	179	+ 3.9
18. Load and Handling	S_b = 2,150 $N_p + N_c$ = 35	289	258	+ 12.0
TOTAL		18,275	17,752	+ 2.9

SECTION 3

SUMMARY OF COST ANALYSIS AND METHODOLOGY

Helicopter cost data were collected from a variety of sources and recurring production cost estimating relationships (CERs) were developed for the systems and subsystems listed in Figure 1.1. The CERs are summarized and the general assumptions made and analytical methodology followed in developing them are discussed in this section. Relevant technical information and the specific data and methodology used in developing each CER are discussed in detail in Section 5.

A. SUMMARY OF COST ESTIMATING RELATIONSHIPS

The recurring production cost estimating relationships developed under this study are presented in Table 3.1. These CERs represent the manufacturer's in-house production costs and/or subcontractor prices associated with each helicopter system or subsystem. Total in-house assembly costs are estimated by a separate equation.*

Helicopter system costs were found to correlate reasonably well with system weights as the independent variable and, as discussed in Section 2, the weight correlates well with a variety of design and performance characteristics. Thus, correlations with other technical and performance characteristics in addition to weight were examined but did not improve the accuracy of weight alone. At later stages of design, other independent variables, such as performance parameters, parts count and commonality, might be included to improve the accuracy of the estimates. However, such data are generally not available during concept formulation or the preliminary design stage when use of this model is intended.

The equations in Table 3.1 represent designs, technologies and manufacturing processes which are currently in use. They may not, for example,

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* These terms are discussed in Section 3D and defined in Appendix A.

Table 3.1

SUMMARY OF
HELICOPTER SYSTEM COST ESTIMATING RELATIONSHIPS
($FY77)

System	Equation*	Notes
1. Wing	$C_1 = 1019W_1^{0.848}Q^{-0.286}$	
2. Rotor	$C_2 = -12,938 + 101W_2Q^{-0.0740}$	
3. Tail		
A. Tail Rotor	$C_{3A} = 102W_{3A}Q^{-0.0740}$	
B. Tail Structure	$C_{3B} = 759W_{3B}^{0.848}Q^{-0.286}$	
4. Body	$C_4 = 860W_4^{0.848}Q^{-0.286}$	
5. Alighting Gear		
Total Wheeled	$C_5 = 84W_5Q^{-0.2176}$	
A. Structure	$C_{5A} = 362W_{5A}Q^{-0.286}$	
B. Controls	$C_{5B} = 159W_{5B}Q^{-0.0896}$	
C. Rolling Assembly	$C_{5C} = 20W_{5C}Q^{-0.0896}$	
or,		
Total Skid	$C_5 = \frac{W_5}{W_4} C_4$	
6. Nacelle	$C_6 = 893W_6^{0.848}Q^{-0.286}$	
7. Propulsion		
A. Powerplant	$C_{7A} = -17,709 + 1219W_{7A}Q^{-0.2345}$	$W_{7A} \leq$ 900 lbs
B. Drive	$C_{7B} = -4795 + 207W_{7B}Q^{-0.0740}$	$W_{7B} \leq$ 700 lbs
	$C_{7B} = -16,423 + 83W_{7B}Q^{-0.0740}$	$W_{7B} \geq$ 1,800 lbs
	$C_{7B} = 19,946 + 83W_{7B}Q^{-0.0740}$	All other 7B
C. Fuel	$C_{7C} = 56W_{7C}Q^{-0.0896}$	
D. Other	$C_{7D} = 145W_{7D}Q^{-0.0896}$	

* Subscripts refer to the numbers in the left hand column. For example, W_1 = Wing Weight.

Table 3.1 (Continued)

SUMMARY OF
HELICOPTER SYSTEM COST ESTIMATING RELATIONSHIPS
($FY77)

System	Equation	Notes
8. Flight Controls	$C_8 = 156W_8Q^{-0.0896}$	
9. Auxiliary Power	$C_9 = 234W_9Q^{-0.0896}$	
10. Instruments		
Total Instruments	$C_{10} = 125W_{10}Q^{-0.0896}$	
A. Equipment	$C_{10A} = 110W_{10}$	
B. Installation, Misc.	$C_{10B} = 140W_{10B}Q^{-0.184}$	
11. Hydraulics	$C_{11} = 91W_{11}Q^{-0.0896}$	
12. Pneumatics	$C_{12} = 137W_{12}Q^{-0.0896}$	
13. Electrical	$C_{13} = 143W_{13}Q^{-0.0896}$	
14. Avionics		
Total Avionics	$C_{14} = 6847 + 125W_{14}Q^{-0.0896}$	
A. Equipment	$C_{14A} = 13,693 + 110W_{14A}$	
B. Installation, Misc.	$C_{14B} = 140W_{14B}Q^{-0.184}$	
15. Furnishings & Equipment	$C_{15} = 69W_{15}Q^{-0.0896}$	
16. Air Conditioning & Heat	$C_{16} = 208W_{16}Q^{-0.0896}$	
17. Anti-Icing	$C_{17} = 213W_{17}Q^{-0.0896}$	
18. Load and Handling	$C_{18} = \frac{W_{18}}{W_4} C_4$	
19. In-House Assembly	$C_{19} = 5.325\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right]Q^{-0.3959}$	Single: $j = \{5C, 7A, 10, 14$
	$C_{19} = 10.775\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right]Q^{-0.3959}$	Tandem: $j = \{5C, 7A, 10, 14$

Where: C = Cumulative average cost for Q units in constant 1977 dollars.
W = Weight of system or subsystem.
Q = Production quantity.

accurately represent new technologies where weight would be significantly reduced while unit cost would change little. Therefore, if the user is interested in assessing new technologies or manufacturing processes, he is advised to consider carefully the detailed discussions of the data and development of the equations which are provided in Section 5.

The approximate percentage of total cost and total weight contributed by each system is indicated in Table 3.2. Although these are approximate and may vary significantly for specific designs, they provide an indication as to the relative cost and weight of the various systems and, also, as to which systems tend to be more costly on a per pound basis. The rank of each system is shown in parentheses next to the percentage.

B. SOURCES OF COST DATA

In order to develop the CERs which were summarized in Table 3.1, a variety of potential sources of cost data were used.

A key source of cost data was The Helicopter Cost Data Source Book(2) which was prepared by SAI for the Cost Analysis Improvement Group (CAIG), Office of the Secretary of Defense (PA&E), and drew upon data provided directly by the DoD, U.S. Army Aviation Systems Command (AAVSCOM) and helicopter manufacturers. This report provides extensive and highly detailed contract cost and quantity information for sixteen different helicopter series produced by five contractors. Such information was invaluable in the development of CERs for the rotor, propulsion (engine and drive), instruments and avionics systems and in the establishment of baseline costs against which all CERs could be compared. However, because these data are proprietary, they are presented and discussed only in general terms so that this report may be distributed without restriction.

Another important source of cost data was subcontractors, who supply major portions of the completed helicopter. Although subcontractors typically would not provide detailed selling prices* for specific items, most

* The subcontractor's "price" is the manufacturer's "cost."

Table 3.2

HELICOPTER SYSTEMS*
APPROXIMATE COST AND WEIGHT PERCENTAGES

System	Approximate Percent of MEW*	Rank	Approximate Percent of Cost**	Rank
Wing	< 1%	(13)	< 1%	(14)
Rotor	17	(3)	12	(3)
Tail	1	(10)	1	(12)
Body	21	(2)	21	(2)
Alighting Gear	5	(5)	2	(9)
Nacelle	1	(10)	3	(7)
Propulsion	31	(1)	32	(1)
Flight Controls	6	(4)	10	(4)
Auxiliary Power Plant	< 1	(13)	1	(12)
Instruments	2	(9)	2	(9)
Hydraulics	< 1	(13)	< 1	(14)
Pneumatics	0	(18)	0	(18)
Electrical	4	(6)	4	(6)
Avionics	3	(8)	5	(5)
Furnishings & Equipment	4	(6)	3	(7)
Air Conditioning & Heat	1	(10)	2	(9)
Anti-Icing	< 1	(13)	< 1	(14)
Load and Handling	< 1	(13)	< 1	(14)
	100%		100%	

* These percentages are based on military helicopters. For commercial helicopters, the furnishings and equipment percentages would probably increase and avionics would probably decrease with the other systems percentages remaining more or less constant.

** Excluding in-house assembly.

were willing to discuss price in terms generally similar to those quoted during preliminary marketing discussions, since they recognized that such prices do not differ markedly from those of their competition. This co-operation provided an understanding of the factors which influence the prices of major subsystems and components.

The following points characterize data furnished by the subcontractors:

- Prices were provided for both commercial and military helicopter systems and, when appropriate, explanations were provided for any differences.
- Prices were provided in 1977 dollars; this eliminated the necessity for application of potentially erroneous inflation factors.
- Explanations were provided concerning how price would normally be expected to vary if changes in design, performance or reliability were specified or if a new technology were introduced.
- Examples were provided regarding the various conditions which influenced prices. These include quantities purchased under a particular contract, inflation, the need to be competitive to win a particular procurement, and the relationships established in former dealings with customers.

While most of the information provided by major subcontractors did not consist of actual prices for specific subsystems or components, the price information which was provided was considered to be representative and accurate enough for the objective of this study. Furthermore, the explanations provided were very useful in relating the costs of major components and subassemblies to total system costs. Thus, cost estimating relationships based on a detailed understanding of the helicopter systems could be developed with the use of this subcontractor information to complement and supplement that obtained from other sources.

Technical reports were found which provided general information such as the percentage of total cost typically represented by a particular system or cost element. This information was used for comparison with data obtained from other sources.

Finally, the earlier SAI report [1] provided extensive detailed cost information on major subsystems and components. This information for transport aircraft served as the basis for some of the helicopter system CERs after analysis and/or discussions with industry personnel confirmed the validity of so doing.

C. BASES FOR COST ESTIMATING RELATIONSHIPS

The CERs summarized in Table 3.1 were developed using parametric analysis and analogies based on information provided by subcontractors or similarities with transport aircraft counterparts, or a combination of these methods, as appropriate.

Parametric analysis generally involved the correlation of detailed historical cost data with weight and other independent variables. When statistically significant results were obtained, these equations became the bases for the cost estimating relationships. If sufficient detailed historical cost data were not available, the information provided by subcontractors served as the basis for developing the CERs. If such data were not available, data for one or several components or subsystems which are similar or analogous to the components or subsystems of interest were used. Sometimes, complexity factors were applied to the analogous data in order to adjust for known differences. In many cases, more than one of these methods were used to develop the final CERs and to evaluate their validity.

Regardless of the source of the cost data or the methodology used to develop the CERs, it was essential that the data be normalized to assure that all reported costs were comparable. Thus, the data were analyzed to determine the following:

- That they reflected the same cost elements so that, for example, Research and Development and Engineering and Tooling costs were not amortized in one while being omitted from another and so that profit was not included in some and excluded from others.
- The quantity produced was considered so that adjustments for learning could be made.
- The years during which the items were produced were considered so that adjustments for inflation could be made.

Inflation and "learning" are two factors frequently cited as influencing cost. Inflation is simply an increase in the volume of money relative to available goods, which results in a substantial rise in the general price level. Under inflation, an item will cost more to produce tomorrow than it does today, using the same mix of material, capital and labor.

For many years, the industry has made use of what have variously been called "learning," "progress," "improvement," or "experience" curves to predict reductions in cost as the number of items produced increases. The learning process is a phenomenon which prevails in many industries; its existence has been verified by empirical data and controlled tests. Although there are several hypotheses on the exact manner in which the learning or cost reduction occurs, the basis of learning-curve theory is that each time the total quantity of items produced doubles, the cost per item is reduced to some constant percentage of the previous cost. Alternative forms of the theory refer to the incremental (unit) cost of producing an item at a given quantity or to the average cost of producing all items up to a given quantity. For example, if the cost of producing the 200th unit of an item is 80 percent of the cost of producing the 100th item, and if the cost of the 400th unit is 80 percent of the cost of the 200th, and so forth, the production process is said to follow an 80 percent unit learning curve. If the average cost of producing all 200 units is 80 percent of the average cost of producing the first 100 units, the process follows an 80 percent cumulative average learning curve. Either formulation of the theory results in a power function which is linear on logarithmic grids.

Although reference is frequently made to a learning curve as some specified percent for a helicopter, it must be recognized that this is a composite of many different learning curves. For example, fabrication labor, minor assembly labor, major assembly labor, material and subcontractor or vendor supplied items may all have different learning curves.

Learning is largely a function of the relative proportions of hand labor and machinery included in the manufacturing process for a particular system. Thus, separate learning curves have been included in each CER so that systems which are primarily manufactured by machinery (e.g., rotors and drives) have relatively flat learning curve slopes, while systems with a large amount of hand labor (e.g., wings, tail and body) have relatively steep slopes.

In summary, inflation acts to increase cost while learning acts to reduce cost. Even though these factors are not related and function independently of one another, their combined effect must be considered by the analyst attempting to make extrapolations from reported cost data. Therefore, the available cost data were first normalized to represent the cumulative average recurring production cost for the first 100 units (CAC_{100}) in 1977 fiscal year dollars ($FY77). This was accomplished as follows:

- Non-recurring costs were identified and removed from the data; in many cases, consultations with helicopter manufacturers assisted in this task.

- Cumulative average cost for 100 units was calculated by computing the average cost for the helicopter lot midpoint nearest 100 units and then estimating the CAC_{100} by using the equation:

$$CAC_{100} = CAC_y \times (Q_{200}^{n} \times Q_y^{-n})$$

Where: y = a number near 100 units for which the CAC could be calculated

Q = quantity

n = the observed learning curve coefficient $(\frac{\log \ell}{\log 2})$

- Reported costs were escalated to $FY77 by using indices provided by AAVSCOM or by DoD, as appropriate.

When only subcontractor-supplied information was available, it was carefully analyzed together with technical and performance data and cost estimates were derived for the various components and subassemblies. System level cost estimates were developed by aggregating cost estimates for the major components and subassemblies based on the relative weights of the components and subassemblies, in accordance with the following equation:

$$C_s/W_s = \Sigma \frac{W_i}{W_s} (C_i/W_i)$$

Where: C = cost

W = weight

s = system

i = each major component or subassembly

For example:

Major Component or Subassembly	Component Percent of Total System Weight	Cost Per Pound
A	25%	\$ 50
B	65	150
C	10	25
Total System	100%	\$ 113

The system level cost per pound estimates were then adjusted to represent first unit and a quantity factor with the appropriate learning curve slope was included to provide a complete recurring production cost estimating relationship.

D. DISCUSSION OF COST ELEMENTS

The recurring production costs estimated by the CERs which were summarized and discussed in general terms above represent only a portion of the manufacturer's total recurring production cost. This may best be understood by referring to a typical breakout of recurring helicopter costs such as that shown in Figure 3.1. The system level CERs reflect only those costs included under in-house production and subcontractor costs; total in-house assembly costs are estimated by a separate CER.

Figure 3.1

RECURRING PRODUCTION COST ELEMENTS
FOR HELICOPTERS

Cost Element*

- In-House Production
  - Fabrication
  - Sustaining Engineering
  - Sustaining Tooling
  - Raw Material
- Subcontractor
  - Outside Production
  - Purchased Equipment
- In-House Assembly
  - Quality Control
  - Minor Assembly
  - Major Assembly
    - Sectional Assembly
    - Installation and Checkout
    - Miscellaneous

---

* See Appendix A for cost element descriptions. The cost elements include direct and indirect costs. Direct costs are those which can be identified with a particular output objective, such as a specific aircraft. Indirect costs are those which are incurred for common or joint objectives and must, therefore, be shared in some equitable manner. Indirect costs are often synonymous with overhead and general and administrative (G&A) costs. For a thorough discussion of indirect costs, see: Martinson, Major Otto B., A Standard Classification System for the Indirect Costs of Defense Contractors in the Aircraft Industry, U.S. Government Printing Office, 1969.

Although CERs for some systems were based on in-house production costs while CERs for other systems were based on subcontractor costs, the actual source of the systems' costs should not significantly alter the CER. A helicopter is composed of parts produced by the helicopter manufacturer and by subcontractors and assembled by the manufacturer or, conversely, the manufacturer could conceivably produce all of the parts. Thus, the assumption is made that the aircraft manufacturer's "make or buy decision" is based primarily on lowest cost. Therefore, the subcontractor costs should closely reflect the manufacturer costs for producing a similar item.

The remaining costs are called "in-house assembly" and are the costs of integrating the various major components and subassemblies into a complete helicopter, ready to be delivered. Thus, in order to arrive at the total recurring helicopter production cost, in-house assembly costs must be added to the system costs estimated using the system level CERs summarized in Table 3.1. A factor for estimating these costs was developed by applying the system level CERs to actual system weights of several helicopters for which aggregate cost data were available.(2) The difference between the actual cost and the estimated cost was assumed to represent the cost of assembly. The results were generally consistent, although observed differences could have been a function of errors in the system level CERs for of differences among assembly costs for different helicopter manufacturers or models.

Thus, by applying the system level CERs and adding the portion estimated for in-house assembly, the total cost of a helicopter is estimated. Unless exceptions are noted, these estimates should be appropriate for either military or commercial helicopters, since their recurring production costs are quite similar. It is, however, important to note that sales price may differ markedly because of different strategies. Commercial prices are generally relatively constant (except for inflation) so that the manufacturer "loses money" until after it passes the breakeven point, after which profits are realized. Military sales usually reflect cost to a much greater extent; even fixed price contracts typically decrease annually, which reflects learning. Thus, to use this model in a market analysis, a profit (say, of 10 percent) needs to be assumed for military helicopters and a breakeven price/quantity needs to be assumed for commercial helicopters.

E. PERCEIVED VALIDITY OF COST ESTIMATING RELATIONSHIPS

Because the quality of the data available for this study ranged from excellent to poor, the confidence which should be placed on the various cost estimating relationships is an important issue. This is, in fact, an issue which is frequently overlooked or ignored in cost analysis studies. One reason for this may be that rating the cost estimating relationships which have been developed in accordance with their perceived validity is necessarily a subjective task.

Where CERs were developed using regression analysis, the coefficient of determination is an indicator of the explained variation from the total variation and, thereby, provides a measure of the validity of the CERs derived. It does not, however, provide any indication of the quantity or of the perceived completeness or accuracy of the data base. Further, no comparable measures of validity are available for the CERs developed by analogy or from general data provided by manufacturers. Therefore, "confidence values" were developed to indicate the perceived quality of the data used in developing the CERs. These confidence values are defined in Table 3.3. They should be useful in indicating areas where potential errors might occur in applying the CERs or where further study could be warranted.

Table 3.4 lists the confidence values assigned to each of the cost estimating relationships summarized in Table 3.1. Confidence values were calculated by prorating values assigned to major components and subassemblies in weighting them according to the following equation:

$$V_s = \sum_i \frac{C_i}{C_s} V_i$$

Where: V = confidence value

C = cost

s = system

i = each major component or subassembly

Table 3.3

BASIS FOR ATTRIBUTING CONFIDENCE VALUES
TO COST ESTIMATING RELATIONSHIPS

Source of Data	Confidence in CER Reliability and Validity
Extensive detailed costs available and accuracy confirmed by industry expert(s)	9.5 - 10
Estimate provided by industry expert(s) and verified by some actual data	9 - 9.5
Similar estimate provided by at least two industry experts or reported actual costs	8 - 9
Estimate provided by one industry expert only	6 - 8
Estimate based on one reported actual cost	5 - 7
Estimate based on judgment using data for similar item as basis for extrapolation	3 - 6
Other assumption	0 - 3

Table 3.4

SUMMARY OF CONFIDENCE VALUES
FOR COST ESTIMATING RELATIONSHIPS

System	Confidence Value
1. Wing	8.0
2. Rotor	9.5
3. Tail	
A. Tail Rotor	5.0
B. Tail Structure	
4. Body	8.0
5. Alighting Gear	
A. Structure	8.0
B. Controls	8.0
C. Rolling Assembly	8.0
or,	
D. Skids	3.0
6. Nacelle	8.0
7. Propulsion	
A. Powerplant	8.0
B. Drive	9.0
C. Fuel	4.0
D. Other	4.0
8. Flight Controls	4.7
9. Auxiliary Power	6.0
10. Instruments	
A. Equipment	5.0
B. Other	6.0
11. Hydraulics	6.5
12. Pneumatics	3.5

Table 3.4 (Continued)

SUMMARY OF CONFIDENCE VALUES
FOR COST ESTIMATING RELATIONSHIPS

System	Confidence Value
13. Electrical	8.0
14. Avionics	
A. Equipment	8.0
B. Other	6.0
15. Furnishings & Equipment	5.7
16. Air Conditioning & Heat	6.0
17. Anti-Icing	3.0
18. Load and Handling	6.0
19. In-House Assembly	8.0
Total*	7.9

* The total confidence value shown is a weighted average based on the estimated percentage of the total cost for each of the helicopter systems provided in Table 3.2.

Confidence values are ordinal numbers which reflect the relative confidence attributed to each cost estimating relationship. They range from a high of 10 to a low of 0. In other words, a CER for which a confidence value of 7.0 has been given is based on data which is assumed to be more reliable than one with a 6.0 rating and less reliable than one with an 8.0 rating.

Each CER represents a best effort. Although CERs with low confidence values might be improved with the availability of more complete information, it is important to note that, in many cases, CERs with relatively low confidence values represent an insignificant portion of the total cost and, therefore, warrant no further effort to validate or improve them unless these systems become of specific interest.

F. EXAMPLE APPLICATIONS OF COST ESTIMATING RELATIONSHIPS

Cost estimates were made for the CH-34A, CH-47A and CH-53A using the equations in Table 3.1. The results are presented in Tables 3.5, 3.6 and 3.7, respectively.

The actual costs shown are exclusive of profit and were adjusted for inflation, quantity and minor weight differences. The reported actual costs included in-house assembly but excluded the rolling assembly, powerplant, instruments and avionics. (Estimates for these items are shown separately; actuals were not available for comparison). When estimated costs were compared with actual costs at this level, it was found that the CH-53A was under-estimated by 8 percent while the CH-34A and CH47A were over-estimated by 1 and 9 percent, respectively. This accuracy should be acceptable for the purpose for which these CERs were intended: i.e., to provide rapid, system level estimates of the cost of conceptual designs.

Furthermore, these examples are felt to provide a strong test of the model because of the diverse nature of the three helicopters, as indicated by the following:

- MEW of the three helicopters ranged from about 6,800 to 23,000 pounds;

Table 3.5

CH-34A COST ESTIMATE
(CAC_{100} in \$FY77)

System	Weight	Cost (\$000)	Cost Per Pound
1. Wing	0	0	-
2. Rotor	1,313	81.4	62
3. Tail	(260)	(22.5)	(87)
Rotor	74	5.4	73
Structure	186	17.1	92
4. Body	1,044	83.6	80
5. Alighting Gear*	(357)	(35.1)	(98)
Structure	309	30.0	97
Controls	48	5.1	106
6. Nacelle	150	16.8	112
7. Propulsion*	(1,452)	(97.7)	(67)
Drive	1,091	84.3	77
Fuel	361	13.4	37
8. Flight Controls	378	39.0	103
9. Auxiliary Power	0	0	-
11. Hydraulics	26	1.6	62
12. Pneumatics	0	0	-
13. Electrical	327	31.0	95
15. Furnishings & Equipment	189	8.6	46
16. Air Conditioning	72	9.9	138
17. Anti-Icing	0	0	-
18. Load and Handling	3	0.2	67
Subtotal	5,571	427.4	77
19. In-House Assembly	-	366.9	-
Total	5,571	794.3	143

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual } CAC_{100}} = \frac{794.3}{784.5} = 1.01$$

Other	Weight	Cost (\$000)	Cost Per Pound
5. Alighting Gear	(118)	(1.6)	(14)
Rolling Assembly	118	1.6	14
7. Propulsion	(1,737)	(701.4)	(404)
Powerplant	1,737	701.4	404
10. Instruments	(108)	(10.3)	(95)
Equipment	76	8.4	111
Installation, Miscellaneous	32	1.9	59
14. Avionics	(269)	(39.3)	(146)
Equipment	188	34.4	183
Installation, Miscellaneous	81	4.9	60
Total Other	2,232	752.6	337
Total MEW	7,803	1,546.9	198

* Remainder of System included under "Other," below.

Table 3.6

CH-47A COST ESTIMATE
(CAC_{100} in \$FY77)

System	Weight	Cost (\$000)	Cost Per Pound
1. Wing	0	0	-
2. Rotor	2,996	203.1	68
3. Tail	0	0	-
Rotor			
Structure			
4. Body	4,487	288.0	64
5. Alighting Gear*	(782)	(76.6)	(98)
Structure	681	66.0	97
Controls	101	10.6	105
6. Nacelle	176	19.2	109
7. Propulsion*	(3,809)	(202.3)	(53)
Drive	3,531	192.0	54
Fuel	278	10.3	37
8. Flight Controls	1,212	125.1	103
9. Auxiliary Power	99	15.3	155
11. Hydraulics	212	12.8	60
12. Pneumatics	0	0	-
13. Electrical	555	52.5	95
15. Furnishings & Equipment	866	39.6	46
16. Air Conditioning	145	20.0	
17. Anti-Icing	34	4.8	141
18. Load and Handling	258	16.6	64
Subtotal	15,631	1,075.9	69
19. In-House Assembly	-	1,871.7	-
Total	15,631	2,947.6	189

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual } CAC_{100}} = \frac{2,947.6}{2,694.5} = 1.09$$

Other	Weight	Cost (\$000)	Cost Per Pound
5. Alighting Gear	(304)	(4.0)	(13)
Rolling Assembly	304	4.0	13
7. Propulsion	(1,342)	(537.9)	(401)
Powerplant	1,342	537.9	401
10. Instruments	(172)	(15.9)	(92)
Equipment	113	12.4	110
Installation, Miscellaneous	59	3.5	59
14. Avionics	(303)	(42.5)	(140)
Equipment	212	37.0	175
Installation, Miscellaneous	91	5.5	60
Total Other	2,124	600.3	283
Total MEW	17,752	3,547.9	200

* Remainder of System Included under "Other," below.

Table 3.7

CH-53A COST ESTIMATE
(CAC_{100} in \$FY77)

System	Weight	Cost (\$000)	Cost Per Pound
1. Wing	0	0	-
2. Rotor	4,489	309.5	69
3. Tail	(673)	(52.7)	(78)
Rotor	367	26.6	72
Structure	306	26.1	85
4. Body	5,260	329.5	63
5. Alighting Gear*	(774)	(76.0)	(98)
Structure	657	63.7	97
Controls	117	12.3	105
6. Nacelle	394	38.0	96
7. Propulsion*	(4,295)	(228.8)	(53)
Drive	3,919	214.9	55
Fuel	376	13.9	37
8. Flight Controls	1,168	120.6	103
9. Auxiliary Power	211	32.7	155
11. Hydraulics	132	8.0	61
12. Pneumatics	0	0	-
13. Electrical	601	56.9	95
15. Furnishings & Equipment	1,289	58.9	46
16. Air Conditioning	234	32.2	138
17. Anti-Icing	77	10.9	142
18. Load and Handling	439	27.5	63
Subtotal	20,036	1,382.2	69
19. In-House Assembly	-	1,189.1	-
Total	20,036	2,571.3	128

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual } CAC_{100}} = \frac{2,571.3}{2,787.3} = 0.92$$

Other	Weight	Cost (\$000)	Cost Per Pound
5. Alighting Gear	(245)	(3.2)	(13)
Rolling Assembly	245	3.2	13
7. Propulsion	(1,762)	(711.8)	(404)
Powerplant	1,762	711.8	404
10. Instruments	(395)	(36.6)	(93)
Equipment	257	28.3	110
Installation, Miscellaneous	138	8.3	60
14. Avionics	(659)	(73.5)	(112)
Equipment	406	58.4	144
Installation, Miscellaneous	253	15.1	60
Total Other	3,061	825.2	270
Total MEW	23,097	3,396.5	147

* Remainder of System included under "Other," below.

- One design (the CH-47A) is a tandem;
- Two manufacturers are represented (Sikorsky built the CH-34A and CH-53A, and Boeing Vertol built the CH-47A).

Finally, it is interesting to note that the model responded well to design differences, as the total estimated costs per pound range from $147 to $200.

SECTION 4

DETAILED SYSTEM WEIGHT ANALYSES

This section provides a detailed discussion of each weight estimating relationship (WER) which was summarized in Table 2.4. Specifically, the items included in each system are described, the design and/or performance characteristics which were examined in arriving at the best correlation with weight are discussed, and alternative WERs are provided. Data which were considered in deriving the WERs are presented in tabular form. Also, where appropriate, the WERs are presented graphically, together with the data points used.

A. WING, TAIL, BODY AND NACELLE SYSTEMS

The structural systems (wing, tail, body and nacelle) are considered together because they have similar designs and use similar materials and methods of fabrication.

Wing System Description

Helicopters typically do not utilize wings, although some more recent designs have incorporated small wing stubs to improve aerodynamic characteristics or to carry military stores. Unlike the wings on fixed wing aircraft, helicopter wings generally include only a simple box structure and do not normally have control surfaces. Therefore, they do not have to accommodate flight controls, hydraulic items or fuel systems. They may serve as fairings or wheel wells for retracting landing gear.

Weight Estimating Relationship

Weights and related information for winged helicopters included in the data base are provided in Table 4.1.

Two explanatory variables, design gross weight (W_g) and wing surface area (S_w), are included in weight estimating relationships for the wings. The WER is:

Equation	r^2
$W_1 = -49.967 + .970S_w + .0212W_g$	0.9385

The covariance for the two independent variables is low ($r^2 = 0.5881$). Surprisingly, design gross weight is a more reliable estimator than wing surface area. An equation using the design gross weight as the only variable provides an r^2 of 0.8775: $W_1 = -99.418 + .0309W_g$. Similarly, an equation using surface area as the variable yields an r^2 of only 0.7689: $W_1 = 136.416 + 2.211S_w$.

Other variables which were investigated, especially dive velocity (V_D), were found to have no explanatory power.

The reliability of design gross weight as an estimator compared to wing surface area should be treated with caution in view of the small number

Table 4.1

WING SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	WING W_1	%MEW	DESIGN GROSS WEIGHT W_g	WING SURFACE AREA S_w	DIVE VELOCITY D_v
269A					
OH-6A					
TH-57A					
OH-58A					
OH-23G					
OH-13S					
BO105					
286					
UH-1H					
H-52A					
UH-19D					
UH-2B					
AH-16C	240	3.5	10,000	59	210
UH-2D					
YAH-64	252	3.2	13,950	71	204
CH-34A					
CH-21C					
YUH-63	349	3.6	15,645	54	218
YUH-61A					
YUH-60A					
SH-3A					
S-67	453	3.9	17,300	98	
AH-56A	539	4.5	18,300	195	
CH-46F					
CH-47A					
CH-54A					
* CH-37A	621	2.9	30,342		
YH-16A					
CH-53A					
347					
Others					
AH-1G	122	2.1	6,600	28	210
AH-56	404	3.4	16,995	130	

---

* Not used in developing WER

of winged helicopters: The data included only seven helicopters with MEWs between 6,000 and 13,000 pounds. Therefore, both variables should be included until there is a greater sample of winged models.

Because there are few data points and two independent variables, the wing WER is not presented graphically.

Tail System Description

A tail system may not be present on all helicopters, since tandem designs do not necessarily require a tail. The usual tail system includes all the aerodynamic surfaces and the mounts for the tail rotor. The helicopter tail is a simple structure similar to the wing structure in that control surfaces are not usually incorporated. The tail rotor and the main rotor are defined similarly.

Weight Estimating Relationships

Weights for the tail structure, tail rotor and their total are summarized in Table 4.2, together with relevant characteristics.

Tail Structure

A single WER was developed for the tail structure, encompassing both single and tandem helicopters. It is:

Equation	r^2	Notes
$W_{3B} = -17.872 + 2.829S_{tt} + K_t$	0.9178	Single: $K_t = 0$ Tandem: $K_t = -111.1$

A reasonable fit using the combined areas of horizontal and vertical tail surface area was achieved. With the exception of the CH-34A and CH-37A, the single helicopters, including the larger ones, were fairly close to the trend line.

The three tandem models for which data were available were significantly lighter than the single helicopters by an average of 111.1 pounds. This is denoted by K_t. As the three tandem models are clustered closely

Table 4.2

TAIL SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	TAIL W_3	%MEW	ROTOR W_{3A}	STRUCTURE W_{3B}	DESIGN GROSS WEIGHT W_g	TAIL SURFACE AREA S_{tt}	MAIN ROTOR CON-FIG.**	TAIL ROTOR RADIUS TRR	NUMI OI BLAI N
269A	9	1.0	5	4	1,600	4.1			
OH-6A	23	1.9	7	16	2,400	12.3		2.1	[illegible]
TH-57A	34	2.2	8	26	2,900	19.9		2.6	[illegible]
OH-58A	32	2.1	10	22	3,000	18.6		2.6	[illegible]
* OH-23G	21	1.1	17	4	2,800			2.8	[illegible]
OH-13S	17	0.9	8	9	2,850	8.7		2.9	[illegible]
BO105	56	2.4	22	34	4,630	19.2		3.1	[illegible]
286	69	2.3	29	40	4,700	19.1		3.3	[illegible]
UH-1H	84	1.6	30	54	6,600	31.3		4.3	[illegible]
H-52A	106	1.9	53	53	7,500	37.0		4.4	[illegible]
UH-19D	101	1.8	60	41	7,100	23.8		4.4	[illegible]
UH-2B	96	1.6	68	28	7,378	15.0		4.0	[illegible]
AH-16C	151	2.2	73	78	10,000	29.0		5.1	[illegible]
UH-2D	216	2.8	104	112	10,187	49.0		4.0	[illegible]
YAH-64	237	3.0	85	152	13,950	66.4		4.2	[illegible]
CH-34A	260	3.3	74	186	11,867	75.3		4.8	[illegible]
CH-21C	162	1.8		162	13,300	101.0	T		
YUH-63	184	1.9	84	100	15,645	57.3		4.8	[illegible]
YUH-61A	344	3.5	76	268	15,313	78.3		5.0	[illegible]
YUH-60A	346	3.4	105	241	16,250	106.4		5.5	[illegible]
SH-3A	222	1.9	99	123	18,064	46.7		5.0	[illegible]
S-67	468	4.0	103	365	17,300	120.0		5.2	[illegible]
AH-56A	287	2.4	130	157	18,300	56.4		5.0	[illegible]
CH-46F							T		
CH-47A							T		
CH-54A	519	2.7	360	159	38,000	42.7		8.0	[illegible]
CH-37A	570	2.7	345	225	30,342	112.0		7.5	[illegible]
YH-16A	133	0.6		133	34,000	100.0	T		
CH-53A	673	2.9	367	306	33,500	93.4		8.0	[illegible]
347							T		
Others									
OH-4A	18		11	7	2,900	7.9		2.6	
H-43B	136			136	6,418	87.8	T		

* Not used in developing WER.

** Single main rotor unless designated T = Tandem.

together without a well-defined slope of their own, it can be hypothesized that their slope is similar to single models.

The only other variable considered was design gross weight, but its r^2 is only 0.5506 and adds nothing to the explanatory power of total surface area.

The WERs for tail structure are presented graphically in Figure 4.1, together with the data from which they were derived.

Tail Rotor

Two WERs were developed for the tail rotor to meet the needs of the user:

Equation	r^2
$\ell n\ W_{3A} = -\ 8.327 + 1.352\ \ell n\ W_g$	0.9497
$W_{3A} = -29.916 + .0102 W_g$	0.9180

The log-linear relationship is the stronger and yields positive values for all tail rotor and gross weight combinations. Due to the small size of tail rotor blades and lack of data for most helicopters, a usable planform area statistic equivalent to that of the main rotor could not be derived. Another possible derived statistic (tail rotor radius multiplied by the number of blades) yields an r^2 of 0.89 in log-linear form, but high covariance with design gross weight prevents it from adding any explanatory power. As in the case of the main rotor, which will be discussed later, separate equations derived by grouping according to the number of blades add no additional information.

The linear equation has a large negative intercept in relation to the design gross weight coefficient, and yields negative values for models with design gross weights of less than 3,000 pounds. It can, however, be aggregated with other systems for future investigation (e.g., all structure systems as a group).

Both the linear and logarithmic tail rotor WERs and the data from which they were derived are presented graphically in Figure 4.2.

Figure 4.1
TAIL STRUCTURE WER

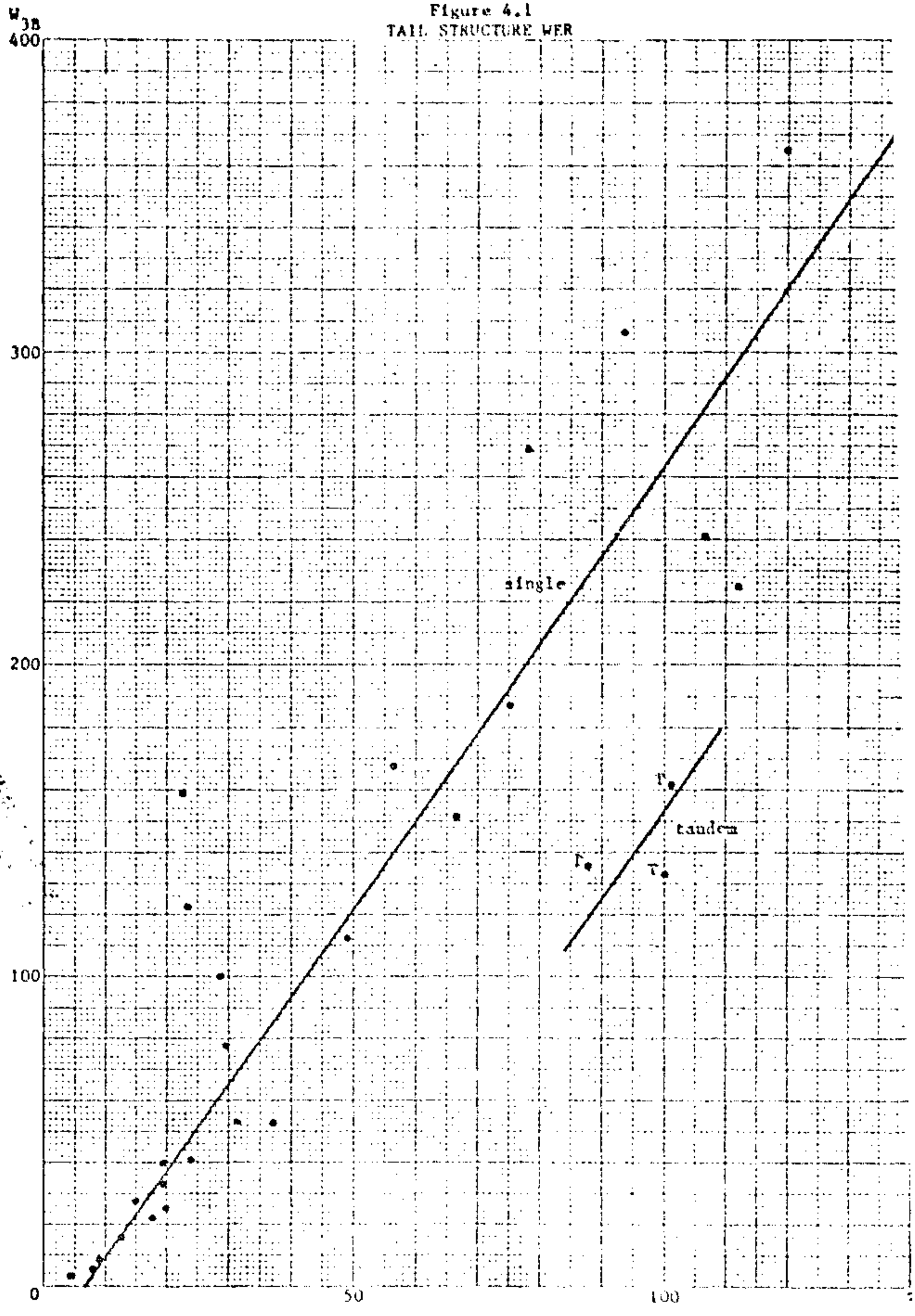
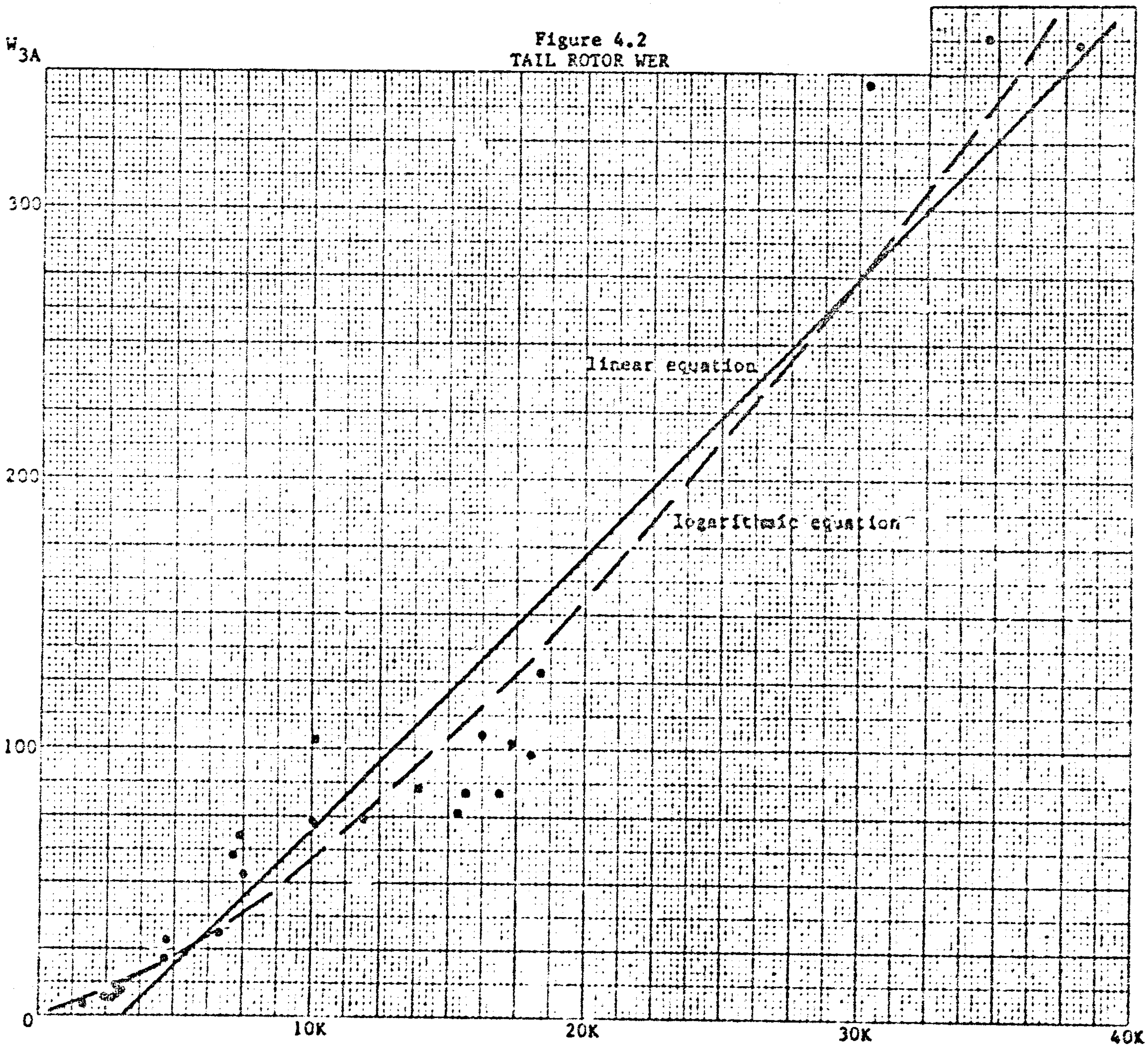


Figure 4.2
TAIL ROTOR WER



Body System Description

The body system consists of the fuselage shell structure, door and window frames, doors, windows, floors, bulkheads, cockpit windshield, and radome. Door actuation mechanisms, airstairs (when installed) and loading ramps are also included.

Body system weights and surface areas are provided in Table 4.3 for helicopters included in the data base.

Weight Estimating Relationship

The following WER was obtained for helicopter bodies:

Equation	r^2
$W_4 = -269.023 + 2.356 S_b$	0.9684

Variances from the trend line due to body configurations (glass surface area, doors, armor plate for attack models, etc.) and other performance characteristics (e.g., number of passengers) are not statistically significant and add nothing to the r^2. Total body surface area is by far the most reliable explanatory variable for body weight. The lb/ft^2 ratio is fairly constant throughout the range of helicopters at approximately 2.2, but declines slightly for the smaller models to about 2.05 due to thinner fuselage structure.

The body WER is presented graphically, together with the data from which it was derived, in Figure 4.3.

Nacelle System Description

The nacelle system includes the engine mount, firewall and cowl structure, engine air inlet, oil cooler scoop and miscellaneous installation hardware.

Nacelle system weights and related characteristics are presented in Table 4.4.

Table 4.3

BODY SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	BODY W_4	%MEW	BODY SURFACE AREA S_b
* 269A	125	12.7	
OH-6A	242	20.1	205
TH-57A	335	21.8	244
OH-58A	332	21.5	247
* OH-23G	248	13.0	
OH-13S	221	11.5	121
BO105	472	20.2	277
286	496	16.6	262
UH-1H	1,035	19.8	626
H-52A	1,263	22.6	849
UH-19D	985	16.9	640
UH-2B	1,259	21.3	609
AH-16C	1,327	19.2	469
UH-2D	1,394	18.3	738
YAH-64	1,311	16.7	606
CH-34A	1,044	13.4	817
CH-21C	1,884	20.6	1,180
YUH-63	1,726	17.7	623
YUH-61A	1,648	16.8	757
YUH-60A	1,729	16.9	805
SH-3A	2,009	17.5	1,112
S-67	1,695	14.4	943
AH-56A	1,872	15.5	847
CH-46F	3,126	23.5	1,452
CH-47A	4,487	25.3	2,150
CH-54A	2,685	14.0	1,199
CH-37C	3,247	15.3	1,553
YH-16A	5,424	23.9	2,300
CH-53A	5,260	22.8	2,262
347	6,259	25.2	2,587
Others			
OH-4A	359		243
H-43B	903		486

* Not used in developing WER.

Figure 4.3
BODY WER

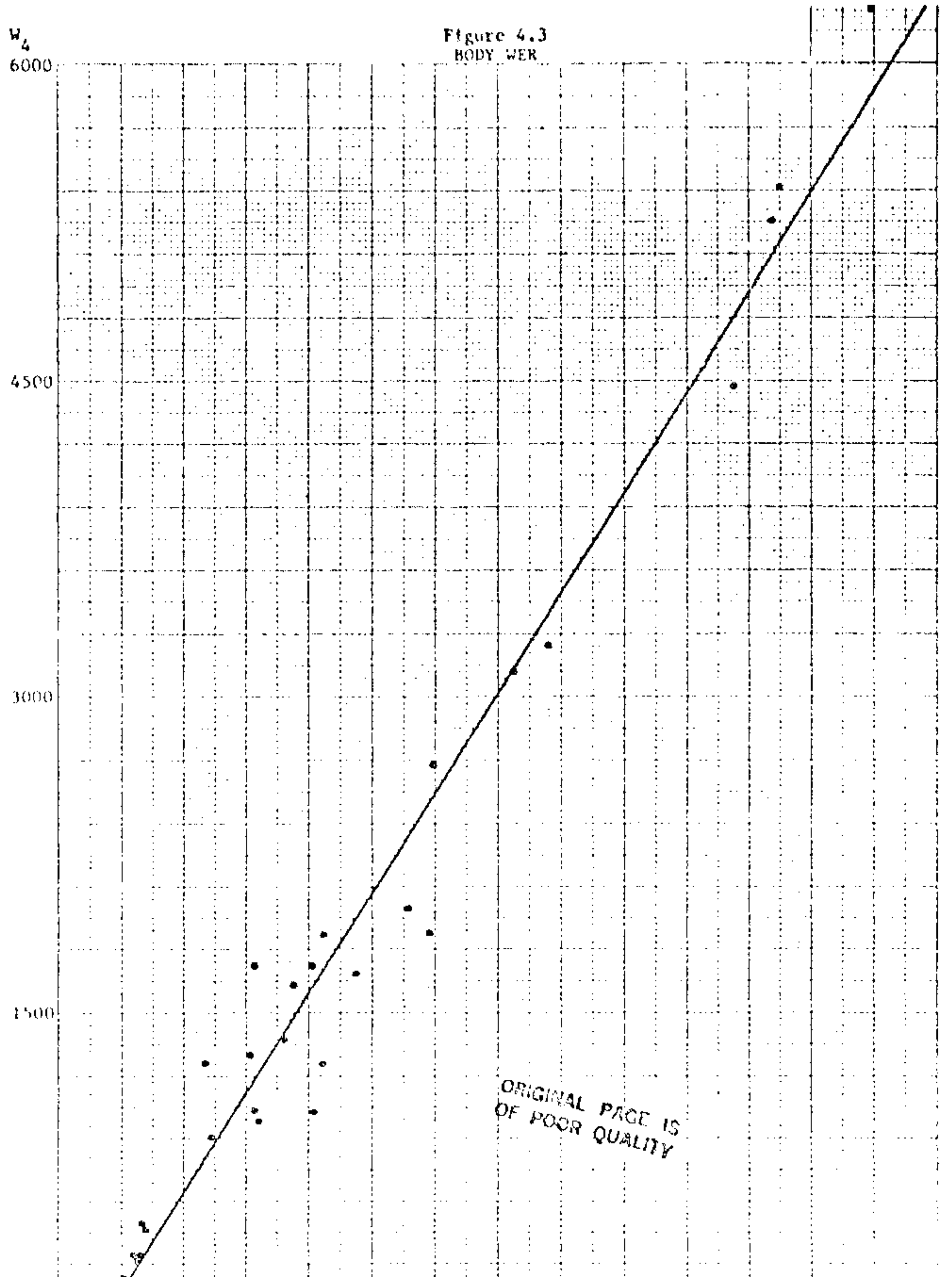


Table 4.4

NACELLE SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

	MODEL	NACELLE W_6	%MEW	NACELLE SURFACE AREA S_n	ENGINE TYPE†	NUMBER OF ENGINES
*	269A	7	0.7		1	1
*	OH-6A	8	0.7		2	1
	TH-57A	32	2.1	50.0	2	1
	OH-58A	36	2.3	50.0	2	1
*	OH-23G	79	4.1		1	1
*	OH-13S	37	1.9		1	1
*	BO105	25	1.1		1	2
*	286	12	0.4		2	1
	UH-1H	114	2.2	82.7	2	1
	H-52A	63	1.1	40.0	2	1
*	UH-19D	147	2.5		1	1
	UH-2B	161	2.7	110.0	2	1
	AH-16C	180	2.6	114.0	2	1
	UH-2D	371	4.9	161.0	2	2
	YAH-64	123	1.6	115.7	2	2
*	CH-34A	150	1.8		1	1
*	CH-21C	89	1.0		1	[illegible]
	YUH-63	252	2.6	105.0	2	2
	YUH-61A	210	2.1	48.0	2	2
	YUH-60A	155	1.5	73.0	1	2
*	SH-3A	131	1.1		2	2
*	S-67	156	1.3	43.0	1	2
	AH-56A	231	1.9	119.0	2	1
*	CH-46F	71	0.5		2	2
	CH-47A	176	1.0	108.0	2	2
*	CH-54A	66	0.3		2	2
*	CH-37A	1,098	5.2		1	2
*	YH-16A	119	0.5		2	2
	CH-53A	394	1.7	178.0	2	2
	347	191	0.8	108.0	2	2
	Others					
*	OH-4A	25			2	1
*	UH-25B	60				
	H-43B	74		29.0	2	1
	AH-1G	147	2.6	104.0	2	1
	UH-1N	197	3.3	104.2	2	2
	AH-1J	203	3.2	117.0	2	2

* Not used in developing WER.

† Engine Types: 1 - Reciprocating; 2 - Turboshaft.

Weight Estimating Relationship

The following WER was derived for the nacelle:

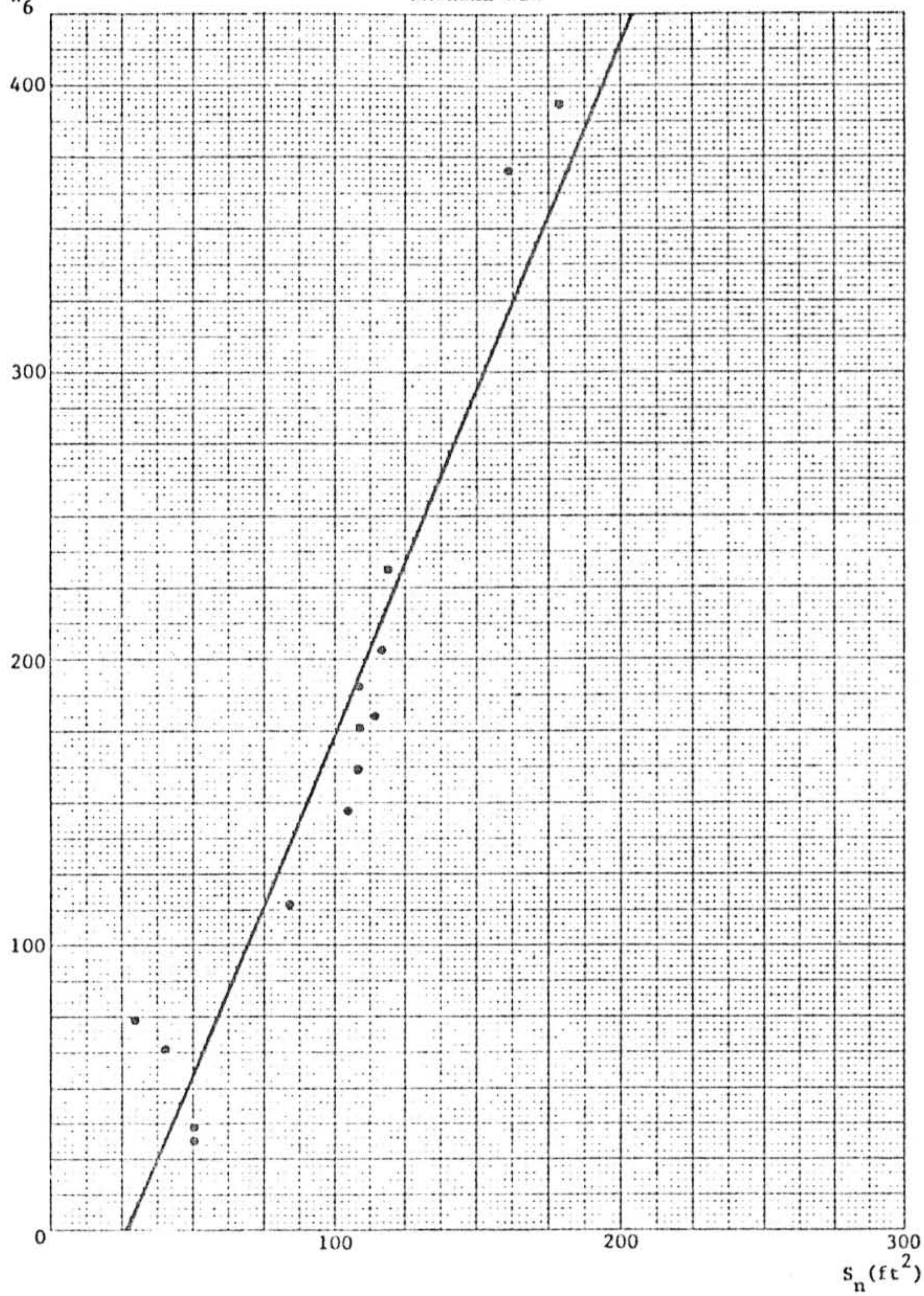
Equation	r^2	Notes
$W_6 = -64.779 + 2.401S_n$	0.9050	External, body-mounted without armor

Surface area is the only reliable estimator for nacelle weight. Models which have their nacelles located in the fuselage (including all the reciprocating-engine helicopters in the sample) have surface areas and weights which are insignificant and, therefore, were not included in the sample. The advanced attack and UTTAS models, whose nacelle weights are generally higher due to armor-plating provided for protection against small-arms fire, and one model (the CH-37A) in which the engine is located on the wing, were also excluded. As there is no significant difference between one- and two-engine models, all the helicopters included can be represented by one equation.

Analysis indicated that no other variable adds any explanatory power to the equation.

The WER for the nacelle is illustrated in Figure 4.4, together with the data from which it was derived.

Figure 4.4
NACELLE WER



B. ROTOR SYSTEM

Rotor System Description

The rotor system consists of the blade assembly and the hub and hinge assembly. The blade assembly includes the interspace structure, leading and trailing edges, tips (if not integral), balance weights, and mounting hardware and blade foldings. The hub and hinge assembly includes the yoke, universal joints, shafting between the rotor system and the drive box, spacers and bushings, lubrication system, fittings, pins, drag brace, retention strap assembly, and fasteners and miscellaneous hardware.

WERs were developed for the complete rotor system and for the blade and hub and hinge assemblies separately.

Weight Estimating Relationships

Weights for the blade and hub and hinge assemblies and for the complete main rotor are presented in Table 4.5, together with other related information for helicopters included in the data base.

The following WERs were obtained for the main rotor system:

Equation	r^2	Notes
$W_2 = -194.685 + 12.164 S_{pl}$	0.9774	Total rotor
$W_{2A} = -88.742 + 6.403 S_{pl}$	0.9713	Blade assembly
$W_{2B} = -105.943 + 5.761 S_{pl}$	0.9626	Hub and hinge

The blade planform surface area (S_{pl}) is the most convenient variable for this system. It is determined by the multiplication of three components: blade length,* blade chord, and number of blades (per hub). Due to high covariance between blade length and chord, and to low correlation between weight and number of blades, a multiple regression with separate coefficients for each S_{pl} component does not improve the fit significantly. There

* Blade length is shorter than blade radius, which is the distance from hub center to blade tip.

Table 4.5

ROTOR SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	ROTOR* W_2	%MEW	BLADE ASSEMBLY W_{2A}	HUB & HINGE* W_{2B}	PLANFORM SURFACE AREA S_{pl}	MAIN ROTOR CON-FIG.**	TYPE***	NUMBER OF BLADES N_b
269A	115	11.7	66	49	20.1		A	3
OH-6A	174	14.5	109	65	26.0		A	4
TH-57A	277	18.0	187	90	31.9		T'	2
OH-58A	281	18.2	190	91	33.9		T'	2
OH-23G	311	16.3	163	148	32.2		T'	2
OH-13S	284	14.7	182	102	32.5		T'	2
BO105	462	19.7	264	198	45.6		R	4
286	726	24.4	427	299	68.3		R	4
UH-1H	742	14.2	406	336	76.9		T'	2
H-52A	785	14.1	425	360	92.5		A	3
UH-19D	786	13.5	422	364	92.5		A	3
UH-2B	1,329	22.5	720	609	124.2		A	4
AH-16C	1,400	20.3	675	725	111.4		T'	2
UH-2D	1,325	17.4	720	605	124.8		A	4
YAH-64	1,207	15.4	664	543	150.0		A	4
CH-34A	1,313	16.8	652	661	129.1		A	4
CH-21C	672	14.7	339	333	76.3	T	A	3
YUH-63	1,656	17.0	979	677	174.9		T'	2
YUH-61A	1,645	16.7	1,052	593	145.1		R	4
YUH-60A	1,558	15.3	809	749	160.0		A	4
SH-3A	2,328*	20.3	1,012	1,316*	186.3		A	5
S-67	2,348	20.0	1,039	1,309	186.3		A	5
AH-56A	2,372	19.6	1,239	1,133	184.0		R	4
CH-46F	1,212*	18.2	459	753*	93.1	T	A	3
CH-47A	1,498	16.9	805	693	136.5	T	A	3
CH-54A	4,052	21.1	2,115	1,937	315.7		A	6
CH-37A	3,251	15.3	1,749	1,502	272.6		A	5
YH-16A	2,268	20.0	1,099	1,169	244.6	T	A	3
CH-53A	4,489*	19.4	2,120	2,369*	348.7		A	6
347	2,527	20.4	1,370	1,157	225.2	T	A	4
Others								
OH-4A	250		157	93	28.8		T'	2
UH-25B	273		136	137	52.8	T	A	3
H-43B	422		351	71	61.3	T	T'	2
CH-53E	6,164*	19.8	2,922	3,242*	451.8		A	7

* Weights include blade foldings; models with foldings (designated *) were normalized by excluding folding weights when calculating WERs.

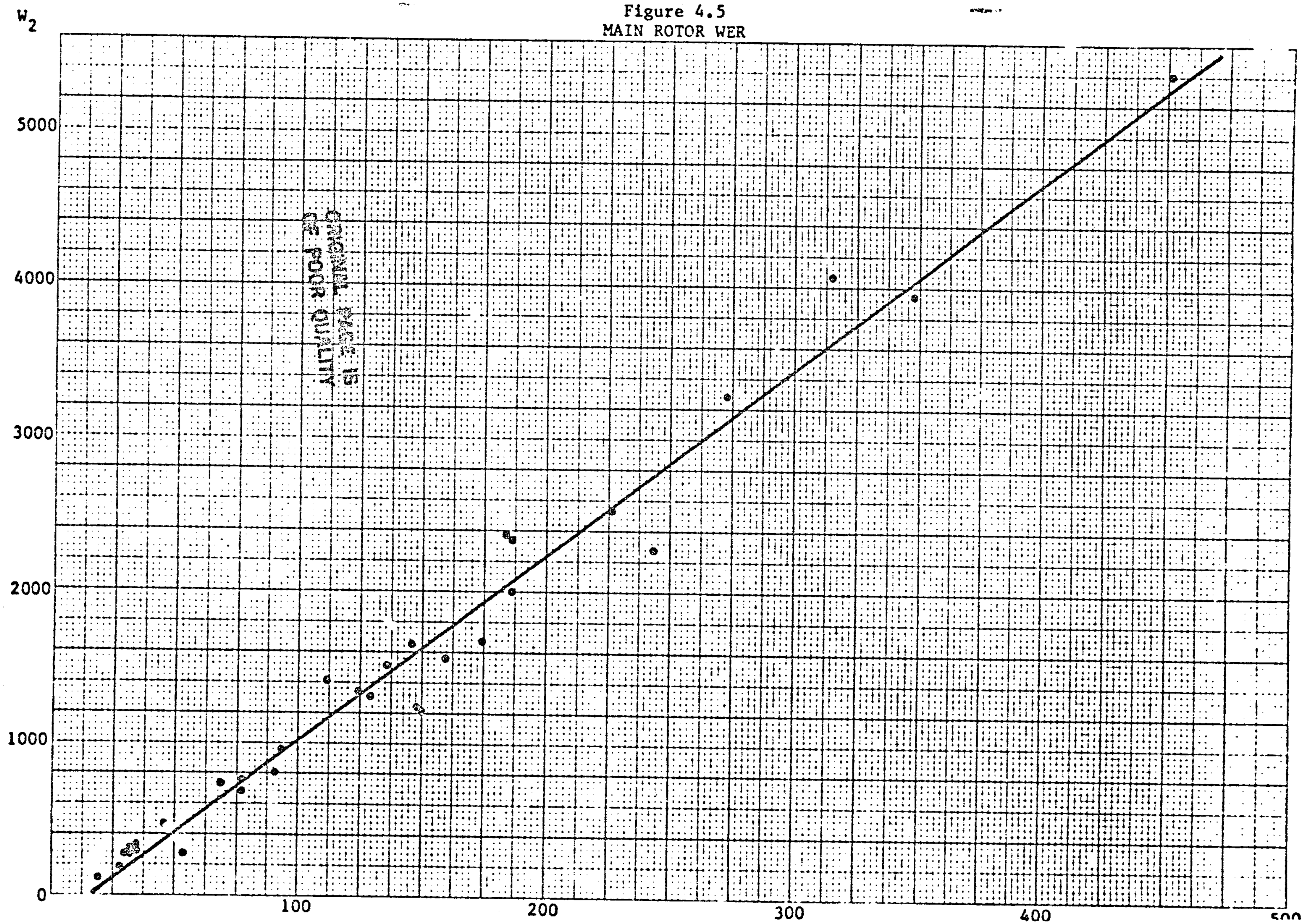
** Single main rotor unless desigrated T = Tandem; note that weights and WERs for tandem models are for one rotor only.

*** A = Articulated; R = Rigid; T'= Teetering.

were no significant differences between rotor type (articulated, teetering, rigid) in determining weight estimates, or between simple and tandem models.

The WER for the main rotor is illustrated in Figure 4.5, together with the data from which it was derived.

Figure 4.5
MAIN ROTOR WER



C. ALIGHTING GEAR SYSTEM

Alighting Gear System Description

Helicopters have two general types of alighting gears. Smaller helicopters (under about 3,000 pounds MEW) usually have skids which are fixed runners and which support the airframe on landing. Larger helicopters generally have fixed wheel-type alighting gears to enable them to be towed on the ground and to take off non-vertically. This system includes landing gear structure, which is made up of struts, side and drag braces, trunnions and attachment fittings. The alighting gear controls include components for braking, steering and retraction (on a few newer models). They also include lines from the cockpit controls to the landing gears. The rolling assembly includes wheels, brakes and tires.

Weight Estimating Relationships

Weights and design characteristics of the helicopter alighting gears included in the data base are provided in Table 4.6.

Separate WERs were derived for skid and wheeled alighting gears:

Equation	r^2	Notes
$W_5 = 161.361 + .0117W_g - 17.480V_{ss}$	0.8061	Skid
$W_5 = 85.875 + .0304W_g$	0.9218	Wheeled
$W_5 = -5.489 + .0342W_g$	0.9347	All

Wheeled gears were reliably estimated by design gross weight. Other pertinent performance criteria (vehicle sink speed--V_{ss}--oleo travel and oleo length) added nothing to the explained variation of designed gross weight. Nor was there any statistical difference between the various subtypes of wheeled gears (conventional, tail, etc.) or between the locations of gears (fuselage, wing, etc.)

Skid-type gears are placed on small helicopters whose MEW does not exceed about 5,000 pounds. Unlike wheeled gears, a second performance characteristic, V_{ss}, improves the r^2 for skid gears significantly. A

Table 4.6

ALIGHTING GEAR SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

	MODEL	ALIGHTING GEAR W_5	%MEW	DESIGN GROSS WEIGHT W_g	VEHICLE SINK SPEED V_{ss}	TYPE OF GEAR	OLEO TRAVEL OLTRV	OLEO LENGTH LOLEO
	269A	53	5.4	1,600	8.00	Skid	3.5	
	OH-6A	70	5.8	2,400	6.00	Skid	3.3	
	TH-57A	45	3.0	2,900	8.00	Skid		
	OH-58A	35	2.6	3,000	8.00	Skid		
†	OH-23G	88	4.6	2,800		Skid		
	OH-13S	54	2.8	2,850	8.00	Skid		
	BO105	94	4.0	4,630	8.25	Skid		
	286	142	4.8	4,700	6.00	Skid		
	UH-1H	121	2.3	6,600	6.00	Skid		
	H-52A	485	8.7	7,500	8.00	Roll	14.0	
	UH-19D	287	5.0	7,100	10.00	Roll	10.6	
	UH-2B	343	5.8	7,378	10.00	Roll	3.5	47.0
	AH-16C	134	1.9	10,000	8.00	Skid		
	UH-2D	424	5.6	10,187	8.00	Roll	2.2	47.0
	YAH-64	396	5.0	13,950	10.00	Roll	16.7	74.0
	CH-34A	475	6.1	11,867	8.00	Roll	11.0	
	CH-21C	522	5.7	13,300	8.00	Roll	11.3	80.0
	YUH-63	497	5.1	15,645	10.00	Roll	14.0	48.3
	YUH-61A	500	5.1	15,313	12.00	Roll	30.0	76.0
	YUH-60A	659	6.4	16,250	10.00	Roll	13.0	71.0
	SH-3A	748	6.5	18,064	8.00	Roll	12.0	37.4
	S-67	656	5.6	17,300	8.00	Roll		12.0
	AH-56A	653	5.4	18,300	10.00	Roll	11.2	55.3
	CH-46F	591	4.4	20,800	8.00	Roll	11.0	45.0
	CH-47A	1,086	6.1	33,000	8.00	Roll	9.2	61.6
*	CH-54A	1,794	9.3	38,000	8.00	Roll		
	CH-37A	983	4.6	30,342	8.00	Roll	13.5	
	YH-16A	1,244	5.5	34,000	8.00	Roll	12.9	32.0
	CH-53A	1,019	4.4	33,500	8.00	Roll	12.0	35.5
*	347	1,114	4.5	42,500	8.00	Roll	11.7	65.6
	Others							
†	OH-4A	43		2,900		Skid		
	UH-25B	185		5,750		Roll		
	H-43B			6,418	5.50	Roll	9.0	23.0

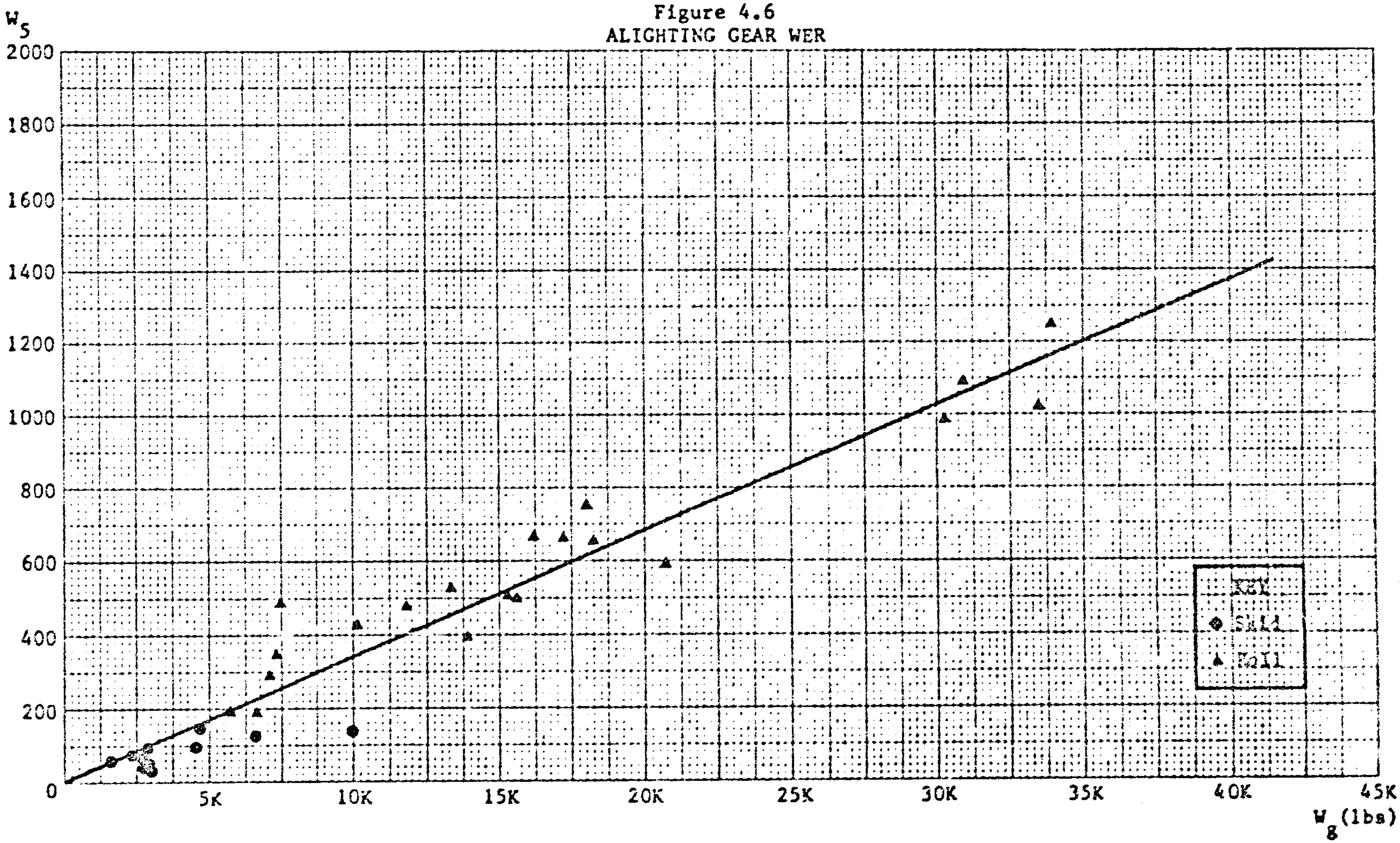
* Not used in developing WER.

† Not used in developing skid WER.

simple regression for skid landing gears on gross weight would be: $W_5 = 10.557 + .0186W_g$. This gives an r^2 of only 0.5660, but adding V_{ss} raises the r^2 to 0.8061. Due to the narrow range of gross weight for skid-type helicopters and to the low r^2, its slope and intercept cannot be regarded as statistically distinct from the wheeled equation. Therefore, both the skid-type and the wheeled models can be represented adequately by the overall equation. V_{ss} adds nothing to this equation.

The combined WER is illustrated in Figure 4.6, together with the data from which it was developed.

Figure 4.6
ALIGHTING GEAR WER



D. PROPULSION SYSTEM

Propulsion System Description

The propulsion system includes three main subsystems: the powerplant, the drive, and the fuel system. The powerplant subsystem includes the dry engine, residual fluids and installation hardware as well as related components: starter, air inductor, exhaust and cooling items, lubrication systems and the engine controls. The drive subsystem includes the gear speed reducers, transmission drive, rotor brake and shaft, and lube system. The fuel subsystem includes the fuel fill and drain system, fuel distribution system, fuel vent plumbing and fuel tanks.

Separate WERs were developed for each of these subsystems.

Weight Estimating Relationships

Weights of each of the main propulsion subsystems are presented in Table 4.7, together with relevant performance and design characteristics for those helicopters included in our data base.

Powerplant

Helicopters were grouped according to the type (reciprocating and turboshaft) and number (single or twin) or engines, in order to achieve satisfactory results. Weight for helicopters in each grouping was then correlated with several independent variables. As indicated by the following WERs, engine horsepower was found to provide the best estimates of power plant weight:

Equation	r^2	Notes
$W_{7A} = 304.483 + 1.027HP_e$	0.9549	Reciprocating, 1 engine
$W_{7A} = 211.546 + .229HP_e$	0.9817	Reciprocating, 2 engines
$W_{7A} = 130.243 + .369HP_e$	0.8263	Turboshaft, 1 engine
$W_{7A} = 408.198 + .192HP_e$	0.9176	Turboshaft, 2 engines

Table 4.7

PROPULSION SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	PROPULSN W_7	%MEW	POWER-PLANT W_{7A}	DRIVE W_{7B}	FUEL W_{7C}
269A	503	51.1	336	142	25 *
OH-6A	341	28.3	192	113	36
TH-57A	396	25.8	194	176	26
OH-58A	419	27.1	165	215	39
OH-23G	771	40.5	551	198	22
OH-13S	845	43.4	588	155	102 *
BO105	804	34.3	348	395	61
286	865	29.0	369	440	56
UH-1H	1,632	31.2	683	658	291
H-52A	1,115	20.0	360	621	134
UH-19D	2,525	43.3	1,244	1,064	217
UH-2B	1,467	24.8	635	733	99 *
AH-16C	1,912	27.7	835	825	252 *
UH-2D	2,365	31.0	805	1,361	199
YAH-64	2,687	34.2	1,089	1,101	497
CH-34A	3,189	40.9	1,737	1,091	361
CH-21C	3,371	36.8	1,809	1,393	169
YUH-63	3,020	31.0	1,093	1,523	404
YUH-61A	2,767	28.2	831	1,576	360
YUH-60A	2,730	26.7	862	1,405	463
SH-3A	2,724	23.8	701	1,763	260 *
S-67	3,466	29.4	941	2,123	402 *
AH-56A	2,895	24.0	969 *	1,680	246
CH-46F	3,235	24.3	951	2,010	274
CH-47A	5,151	29.0	1,342	3,531	278
CH-54A	6,857	35.7	2,185	3,797	875
CH-37A	8,419	39.6	5,516 *	2,567	336
YH-16A	7,822	34.5	3,706 *	3,679	437
CH-53A	6,057	26.2	1,762	3,919	376
347	6,881	27.7	1,741	3,796	1,344
Others					
OH-4A	390		199	159	32 *
UH-25B	1,667		1,020	587	60 *
H-43B	1,542		697 *	730	115 *

* Not used in developing WER.

Table 4.7 (Continued)

PROPULSION SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	HORSE-POWER HP_e	DESIGN GROSS WEIGHT W_g	FUEL QUANTITY G	ENGINE TYPE†	NUMBER OF ENGINES	ENGINE RPM	GEAR BOX RATIO GBR
269A	180	1,600		1	1	2,900	6.01
OH-6A	250	2,400	62	2	1	6,180	12.80
TH-57A	317	2,900	76	2	1	36,050	101.73
OH-58A	317	3,000	73	2	1	36,050	101.73
OH-23G	305	2,800	46	1	1	3,200	8.66
OH-13S	260	2,850		1	1	3,200	9.00
BO105	600	4,630	154	1	2	6,000	14.10
286	550	4,700	82	2	1	6,230	17.55
UH-1H	1,103	6,600	211	2	1	21,189	67.50
H-52A	1,050	7,500	325	2	1	18,970	89.50
UH-19D	800	7,100	175	1	1	2,400	11.31
UH-2B	1,250	7,378		2	1	19,500	70.41
AH-16C	2,050	10,000		2	1	14,500	49.00
UH-2D	2,500	10,187	276	2	2	6,000	20.80
YAH-64	3,000	13,950	353	2	2	20,000	69.77
CH-34A	1,525	11,867	263	1	1	2,500	11.31
CH-21C	1,425	13,300	300	1	1	2,700	9.71
YUH-63	3,000	15,645	343	2	2	20,000	72.46
YUH-61A	3,000	15,313	352	2	2	20,000	67.60
YUH-60A	3,036	16,250	343	1	2	20,000	76.04
SH-3A	2,500	18,064		2	2	18,966	93.46
S-67	3,000	17,300		1	2	19,700	93.46
AH-56A	3,925	18,300	438	2	1	13,600	55.30
CH-46F	2,600	20,800	380	2	2	19,500	73.77
CH-47A	4,400	33,000	620	2	2	14,750	66.00
CH-54A	9,600	38,000	1,342	2	2	9,000	48.54
CH-37A	4,200	30,342	410	1	2	2,600	14.01
YH-16A	3,600	34,000	700	2	2	6,400	97.61
CH-53A	5,700	33,500	638	2	2	13,600	73.51
347	7,500	42,500	1,200	2	2	15,690	64.00
Others							
OH-4A	250	2,900		2	1	36,050	15.21
UH-25B	525	5,750		1	1		
H-43B	860	6,418		2	1	6,680	28.41

† Engine Types: 1 - Reciprocating; 2 - Turboshaft.

The WERs are presented graphically together with the data from which they were derived in Figure 4.7.

Although design gross weight gave r^2s similar to those obtained using engine horsepower for single engine helicopters, engine horsepower was found to be much better for two-engine models, especially for turboshaft models. Due to high covariance, neither weight nor any other related characteristic (e.g., engine RPM, gear-box ratio) improved the coefficient of variation significantly. Both engine horsepower and design gross weight yielded significantlv different slopes for single engine, reciprocating models, making a single equation for all categories inappropriate.

Separate equations for engines and powerplant residual (air induction, exhaust and cooling, engine controls, starter system) were also obtained.

For the engines, the following WERs were derived:

Equation	r^2	Notes
$W_{7A'} = 243.592 + .796HP_e$	0.9492	Reciprocating, 1 engine
$W_{7A'} = 161.776 + .192HP_e$	0.9226	Reciprocating, 2 engines
$W_{7A'} = 98.120 + .243HP_e$	0.8458	Turboshaft, 1 engine
$W_{7A'} = 249.094 + .179HP_e$	0.9540	Turboshaft, 2 engines

As engines comprise 75 to 80 percent of the powerplant, the WERs are comparable. Correlations are also similar. As with the entire powerplant, engine correlations were lower for gross weight and RPM for all model types.

Separate equations for the powerplant residual were harder to derive, but workable WERs for single engine models were obtained:

Equation	r^2	Notes
$W_{7A''} = 60.891 + .230HP_e$	0.7854	Reciprocating, 1 engine
$W_{7A''} = 32.123 + .126HP_e$	0.5853	Turboshaft, 1 engine

WERs for two-engine models could not be derived due to lack of correlation with any relevant performance characteristic. Nonetheless, the following constants were calculated:

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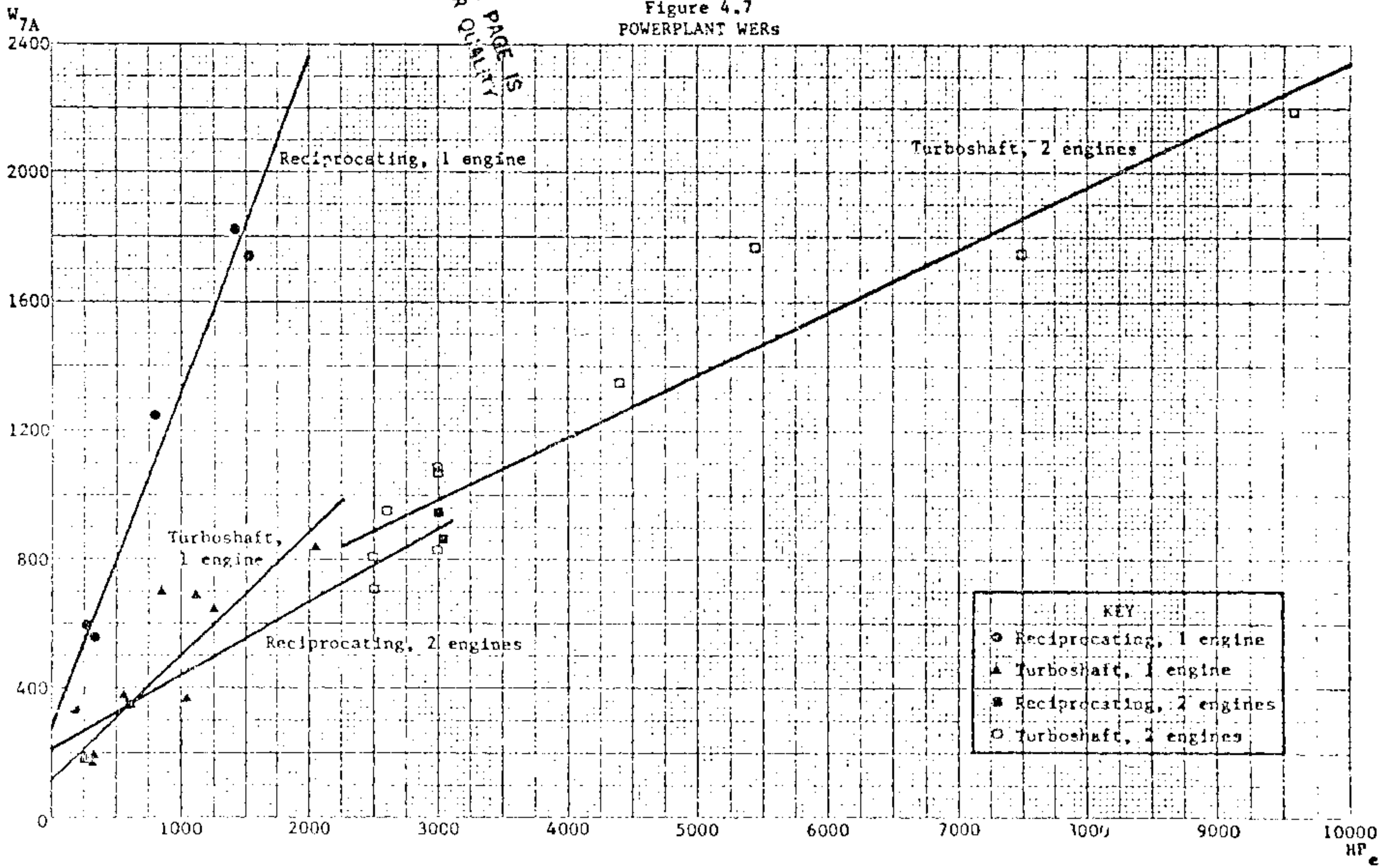
Figure 4.7
POWERPLANT WERs



Weight Estimate	Standard Deviation	Notes
$W_{7A''} = 141$	125	Reciprocating, 2 engines
$W_{7A''} = 241$	65	Turboshaft, 2 engines

In general, separate equations for engines and powerplant residuals do not improve the estimates.

Drive

A single WER was found to be appropriate for all drive systems:

Equation	r^2
$W_{7B} = -35.551 + .101W_g$	0.9657

Design gross weight is the best explanatory variable for this subsystem, yielding a high r^2. Engine horsepower did not have as high a coefficient of determination in any category (type of engine, number of engines, etc.) but was a fairly good estimator, with r^2s ranging from 0.70 for two-engine, turboshaft models to 0.93 for turboshaft, single engine models. Results for RPM and gear-box ratio were highly erratic. The r^2s for the variables considered are summarized below:

Type	Number of Engines	Design Gross Weight	Engine Horse Power	RPM	Gear Box Ratio	Number HC in Sample
Recip.	1	.9055	.8636	.6777	.5369	6
Recip.	2	.8814	.8192	.8146	.9540	3
Turbo.	1	.9713	.9270	.1681	.0001	11
Turbo.	2	.9359	.7008	.1459	.1104	10

Gross weight is the best estimator. As the differences in slopes and intercepts of each case above are statistically insignificant, an overall equation for the drive system is appropriate, as indicated above. Separate equations for the other performance characteristics vary widely and yield weak overall results when combined.

The drive system WER and the data upon which it is based are presented in Figure 4.8.

Fuel System

The following WER was derived for fuel systems:

Equation	r^2
$W_{7C} = 10.974 + .790G$	0.7732

Fuel capacity (gallons) is the only candidate variable with an acceptable correlation. Number of tanks was also considered separately. Some differences were detected between protected and unprotected tanks, but separate equations for tanks alone had weak correlations (0.5 to 0.6). Also, tarks comprise only a fraction (25 to 30 percent) of the fuel system, which further dilutes the importance of tank protection as a variable. It is suggested that weights of fuel systems with protected (unprotected) tanks be raised (lowered) by a factor of 0.25. Many models have both types of tanks, and their weight estimates should be adjusted accordingly.

The fuel system WER and the data upon which it is based are presented in Figure 4.9.

Figure 4.8
DRIVE SYSTEM WER

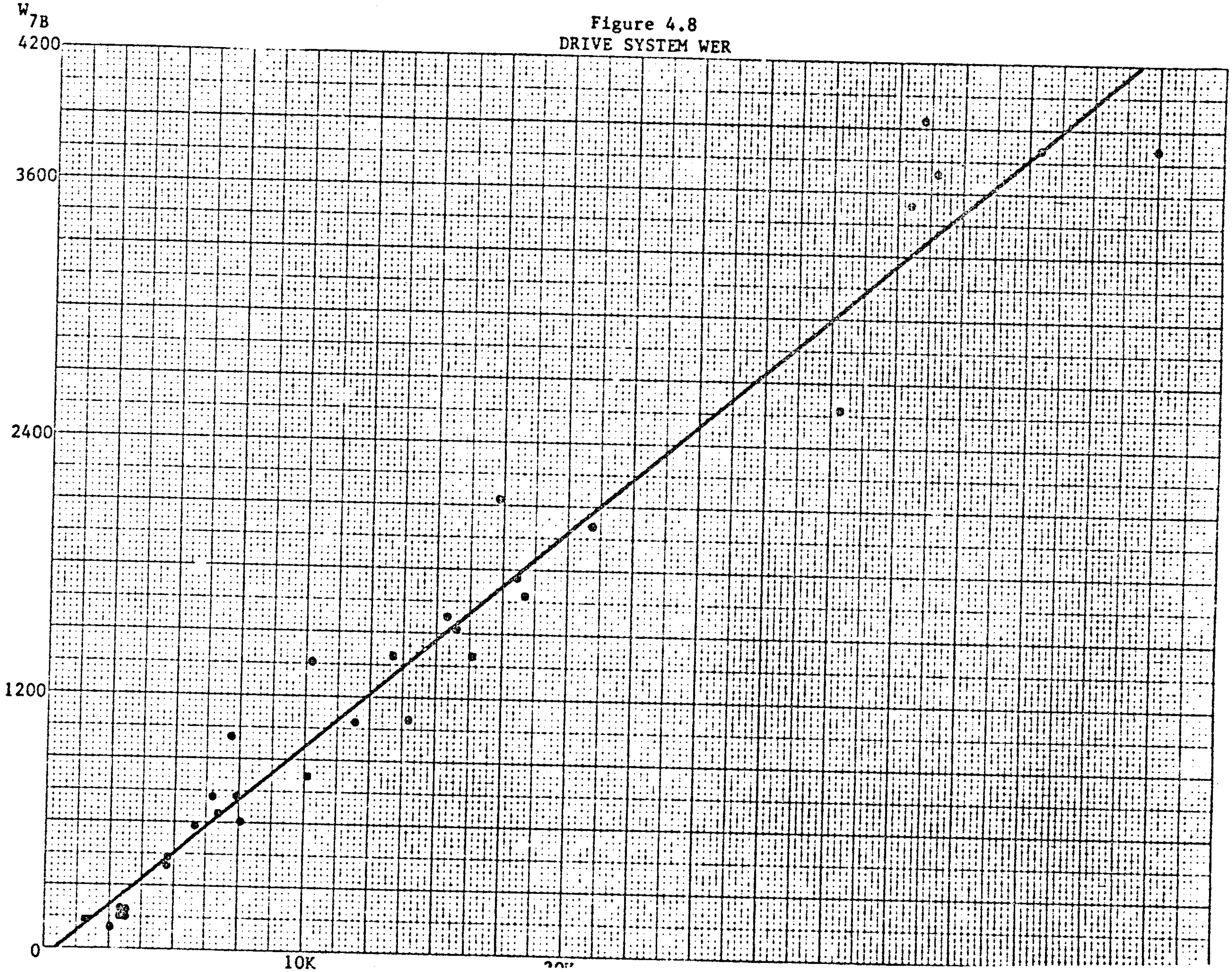
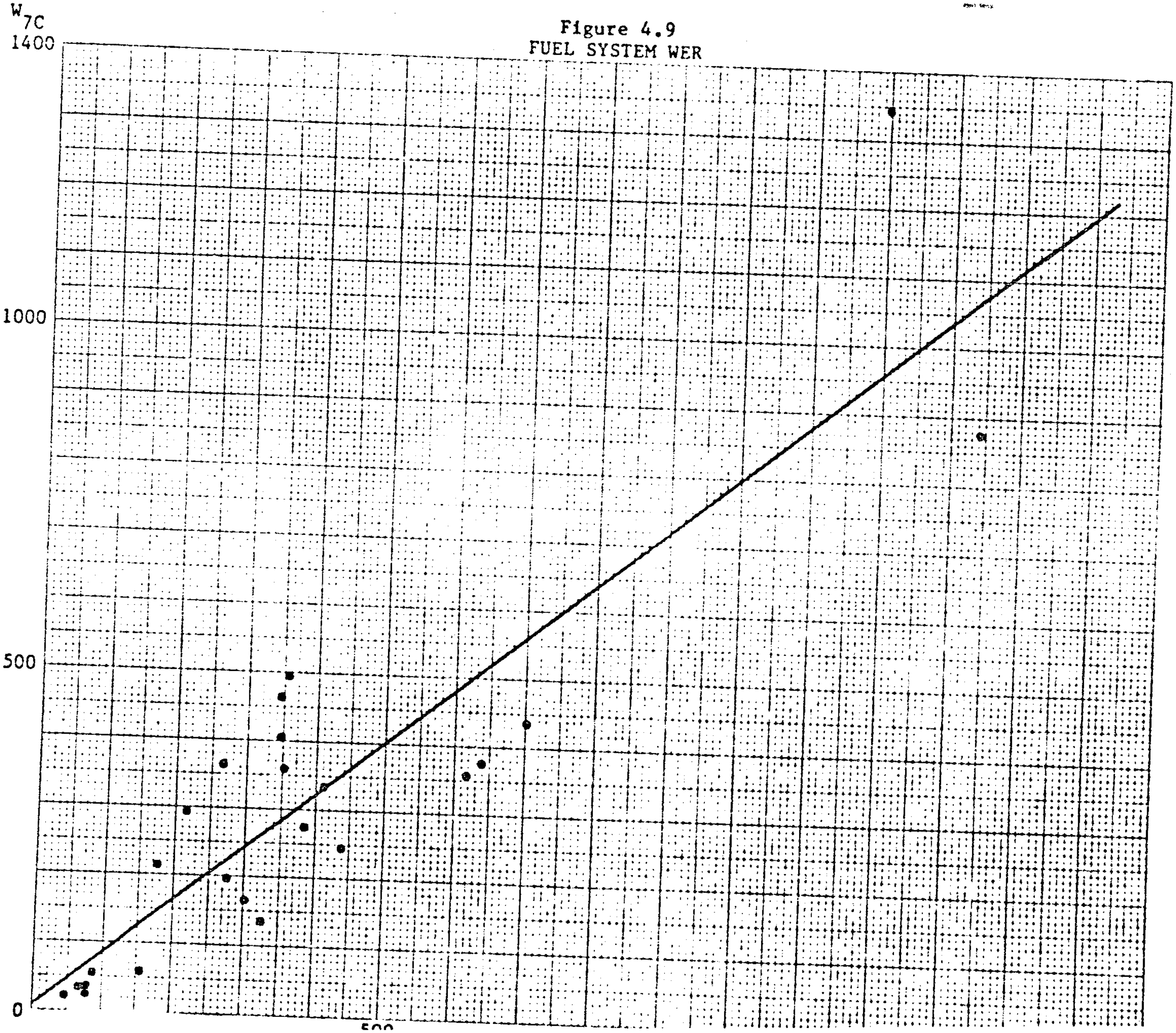


Figure 4.9
FUEL SYSTEM WER



E. FLIGHT CONTROLS SYSTEM

Flight Controls System Description

The helicopter flight controls system includes: cabin controls (cyclic control column, collective pitch levers and rudder or tail rotor pedal); mechanical operating mechanism (swash plate, stabilizing bar, linkages, bearings and levers, bellcranks); hydraulic controls; fluid; and miscellaneous hardware.

Weight Estimating Relationship

Weights and related information for the flight controls system are provided in Table 4.8.

Design gross weight is the only reliable estimator for flight controls weight. The WER is presented below:

Equation	r^2
$W_8 = 62.025 + .0334W_g$	0.9475

Even though flight controls are strongly related to the main rotor function, rotor characteristics add no additional explanatory power to the equation; varying rotor types (hingeless, articulating, etc.) make no statistical difference.

Weights for the tandem models are consistently higher than for the overall trend line by about 55 pounds, but this is not significant in view of the average flight control weight (535 pounds) and standard deviation (373 pounds). The actual tandem weights would fall well within any standard confidence intervals. Similarly, data for UTTAS and AAH models (weakly) suggest higher weights than those predicted by the equation; the differences are, however, not significant.

Finally, the presence of wings (as a flight control device) is not significant. Although one might expect flight controls weights to be affected by wings, models with wings appear on both sides of the trend line.

The WER and the data from which it was derived are presented in Figure 4.10.

Table 4.8

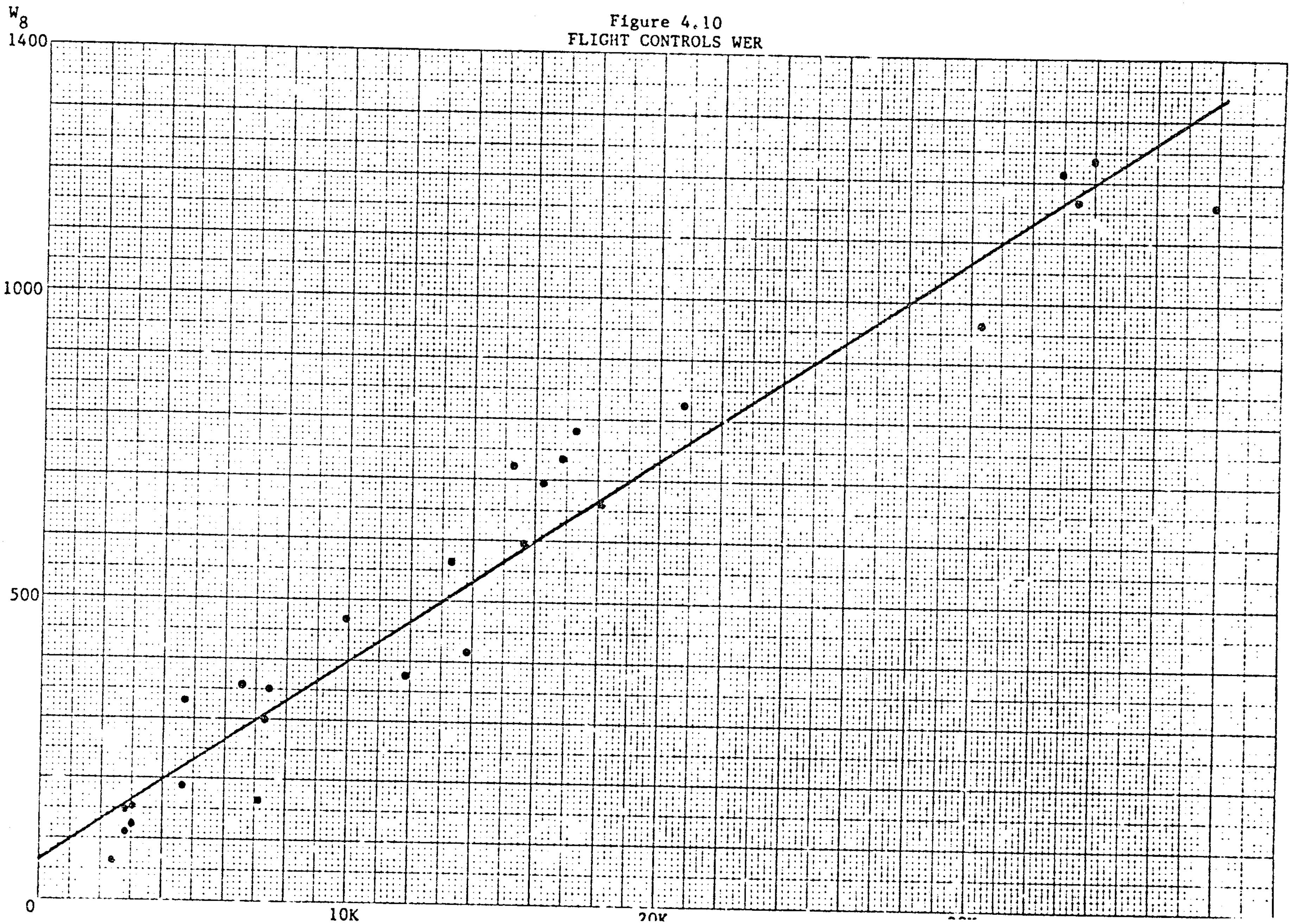
FLIGHT CONTROLS SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	FLIGHT CONTROLS W_8	%MEW	DESIGN GROSS WEIGHT W_g	MAIN ROTOR TYPE †	TANDEM	WING
269A	51	5.2	1,600	1		
CH-6A	65	5.4	2,400	1		
TH-57A	133	8.7	2,900	2		
OH-58A	125	8.1	3,000	2		
OH-23G	108	5.7	2,800	2		
OH-13S	153	7.9	2,850	2		
BO105	189	8.1	4,630	4		
286	327	11.0	4,700	3		
UH-1H	357	6.8	6,600	1		
H-52A	353	6.3	7,500	1		
UH-19D	164	2.8	7,100	1		
UH-2B	301	5.1	7,378	1		
AH-16C	469	6.8	10,000	2		W
UH-2D	300	3.9	10,187	1		
YAH-64	419	5.3	13,950	1		W
CH-34A	378	4.8	11,867	1		
CH-21C	561	6.1	13,300	1	T	
YUH-63	596	6.1	15,645	2		W
YUH-61A	721	7.3	15,313	4		
YUH-60A	694	8.2	16,250	1		
SH-3A	654	5.7	18,064	1		
S-67	780	6.6	17,300	1		W
* AH-56A	1,021	8.5	18,300	3		W
CH-46F	828	6.2	20,800	1	T	
CH-47A	1,212	6.8	33,000	1	T	
CH-54A	1,161	6.0	38,000	1		
CH-37A	965	4.5	30,342	1		
YH-16A	1,239	5.5	34,000	1	T	
CH-53A	1,168	5.1	33,500	1		
* 347	1,921	7.7	42,500	1	T	
Others						
AH-56	735	6.2	16,995	3		W

* Not used in developing WER.

† Rotor Types: 1 - Articulating; 2 - Teetering; 3 - Rigid; 4 - Semi-Rigid.

Figure 4.10
FLIGHT CONTROLS WER



V. INTEGRATED PNEUMATIC SYSTEM

Integrated Pneumatic System Description

Integrated pneumatic system (IPS) is a term often applied to the combined auxiliary power, pneumatic, air conditioning, and anti-icing systems. Although these systems are treated separately in Military Standard 1374A (except for the pneumatic system, which is combined with the hydraulic system), manufacturers and their major subcontractors consider them as part of a single system because of their commonality.

Weights and design characteristics are presented in Table 4.9 for the auxiliary power system. The air conditioning and anti-icing systems are presented in Table 4.10.

Auxiliary Power System Description

The auxiliary power system supplies all power for ground operations in lieu of ground support equipment. These operations include: cabin ground air conditioning, engine starting, and driving a generator for electric power.

Weight Estimating Relationship

The WER provided for auxiliary power systems is simply based on the average weight observed for those helicopters which utilize them. It is:

Equation

$$W_9 = 157$$

As indicated, the average auxiliary power system weight for the ten helicopters* on which it is included is 157 pounds, with a standard deviation of only 39 pounds. Thus, an average value can be assigned to the system with fairly high confidence.

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* The helicopters have a design gross weight of over 13,000 pounds, with an average of approximately 24,750 pounds.

Table 4.9

AUXILIARY POWERPLANT SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	AUXILIARY POWER-PLANT W_9	%MEW
269A		
OH-6A		
TH-57A		
OH-58A		
OH-23G		
OH-13S		
BO105		
286		
UH-1H		
H-52A		
UH-19D		
UH-2B		
AH-16C		
UH-2D		
YAH-64	135	1.7
CH-34A		
CH-21C		
YUH-63	137	1.4
YUH-61A	193	2.0
YUH-60A	194	1.9
SH-3A		
S-67		
AH-56A	136	1.1
CH-46F	106	0.8
CH-47A	99	0.6
CH-54A	183	1.0
CH-37A		
YH-16A		
CH-53A	211	0.9
347	177	0.7

Table 4.10

AIR CONDITIONING AND ANTI-ICING SYSTEMS WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	AIR CONDITIONING W_{16}	%MEW	ANTI-ICING W_{17}	%MEW	W_{16+17}	BODY SURFACE AREA S_b
269A	11	1.1			11	
OH-6A	9	0.7	1	0.1	10	205
TH-57A	27	1.8			27	244
OH-58A	25	1.6			25	247
OH-23G	4	0.2			4	
OH-13S	40	2.1			40	121
BO105						277
286	14	0.5			14	262
UH-1H	44	0.8			44	626
H-52A	88	1.6	9	0.2	97	849
UH-19D	77	1.3			77	640
UH-2B	25	0.4	56	0.9	81	609
AH-16C	76	1.1			76	469
UH-2D	35	0.5	33	0.4	68	738
YAH-64	99	1.3	5	0.1	104	606
CH-34A	72	0.9			72	817
CH-21C	137	1.5			137	1,180
YUH-63	98	1.0	6	0.1	104	623
YUH-61A	78	0.8	33	0.3	111	757
YUH-60A	58	0.6	28	0.3	86	805
SH-3A	86	0.8	23	0.2	109	1,112
S-67	126	1.1			126	943
AH-56A	75	0.6	42	0.3	117	847
* CH-46F	127	1.0	130	1.0	257	1,452
CH-47A	145	0.8	34	0.2	179	2,150
CH-54A	94	0.5	20	0.1	114	1,199
CH-37A	176	0.9			176	1,553
YH-16A	165	0.7			165	2,300
* CH-53A	234	1.0	77	0.3	311	2,262
347	155	0.6	47	0.2	202	2,587

* Not used in developing WER.

An attempt to develop an equation using regression analysis was unsuccessful. For example, an equation obtained using design gross weight as an independent variable ($W_9 = 158.42 + .000756W_g$) had an r^2 of only 0.0431.

Pneumatic System Description

Curiously, none of the helicopter weight statements examined indicated the existence of a pneumatic system. Thus, the following description is for fixed wing aircraft but should be applicable to helicopter designs which might incorporate a pneumatic system.

The pneumatic system includes all heat exchangers and ducting, which carries pressurized air from each of the main engines and from the auxiliary power unit (APU). The pneumatic system provides compressed air for cabin pressurization, air conditioning and ventilation, engine starting, ice prevention and turbine-driven supplementary or emergency hydraulic power.

Because of the complete absence of data, a WER was not derived for the pneumatic system.

Air Conditioning and Anti-Icing Systems Description

The air conditioning system, in addition to supplying conditioned air to the cabin, heats the cargo compartment and supplies conditioned air for avionic and electrical load center cooling.

Anti-icing functions can be performed either by hot bleed air or by electrical heat. Bleed air systems include all ducting from the main pneumatic source and inner skins, which form the hot air cavities. Electrical systems include the electrical blankets fastened to the outer surfaces of critical items, plus all wiring and controls.

Weight Estimating Relationship

The air conditioning and anti-icing systems were combined to develop a weight estimating relationship because the combination yielded substantially better results. The combined WER is:

Equation	r^2
$W_{16+17} = 28.844 + .0730S_b$	0.8172

Total body surface area is the best independent variable for estimating the combined weight of the air conditioning and anti-icing systems. The function is strongly linear; logarithmic transformations of the data result in lower correlations.

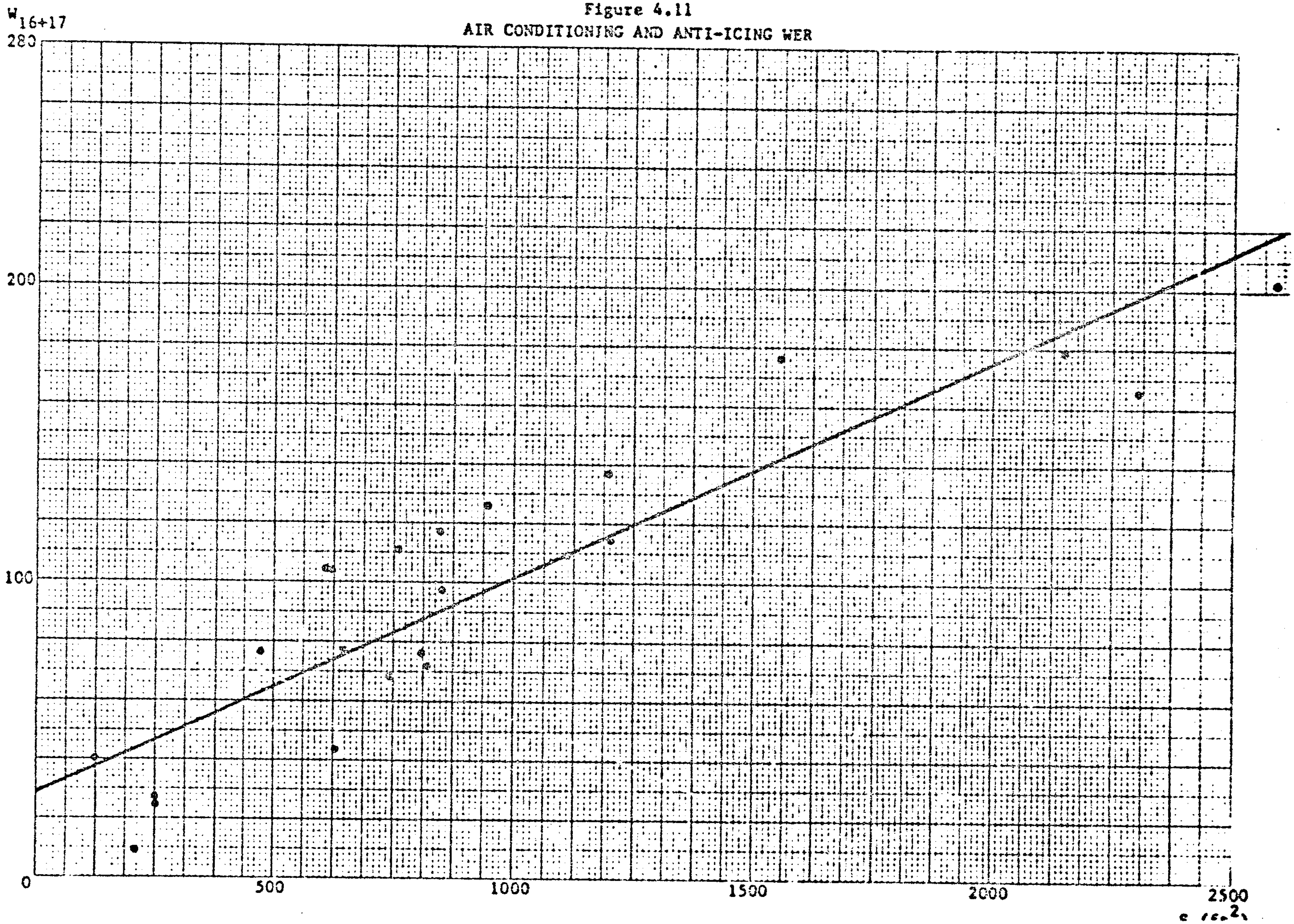
The other variable considered was design gross weight, which resulted in the following equation: $W_{16+17} = 28.442 + .00414W_g$. The r^2 was 0.7785 and was not improved by use of a logarithmic equation with the design gross weight variable. Despite the high correlation, design gross weight as a second independent variable raises the r^2 only to 0.8394, because of its high covariance with body surface area (0.82).

The following results were obtained for the air conditioning system when it was considered independently: $W_{16} = 22.078 + .0698S_b$ and $W_{16} = 23.358 + .00397W_g$. R^2s of 0.7593 and 0.6855, respectively, were calculated for these equations. As in the case of the electrical system, the lower r^2 with design gross weight for both W_{16+17} and W_{16} is due to the wide variance for models over 20,000 pounds.

A separate equation for anti-icing systems in unobtainable due to the lack of significant slope and correlation with any relevant explanatory variable. For example, $W_{17} = 19.938 + .000837W_g$ has an r^2 of only 0.0908. An attempt to represent the anti-icing as a constant was not successful because of its large standard deviation (33.17 pounds) relative to its average weight (36.27 pounds). As anti-icing weight statistics are almost random in nature, they could be easily integrated with air conditioning weights without loss of explanatory power.

The combined air conditioning/anti-icing WER is presented graphically in Figure 4.11.

Figure 4.11
AIR CONDITIONING AND ANTI-ICING WER



G. INSTRUMENTS AND AVIONICS SYSTEMS

Although they are separate systems, instruments and avionics are discussed together because they have many similarities in terms of the nature of the components they employ.

Instruments System Description

Instruments perform basic monitoring and warning functions associated with the flight of the helicopter: electrical, hydraulic and pneumatic systems operation, engine operation and fuel quantity. The instruments system includes cockpit indicators and warning lights, transducers, signal inputs, circuitry, and the monitoring devices.

Weight Estimating Relationship

Weights and related design characteristics for the instruments system are provided in Table 4.11.

Several variables related to instrument system weight were analyzed. Engine horsepower and fuel capacity were considered because they are related to key instrument functions. Design gross weight was considered because of its demonstrated explanatory power for other systems. Although correlations were similar for all three, engine horsepower was found to be the best. The WER using it as the independent variable is:

Equation	r^2
$W_{10} = 50.507 + .0267HP_e$	0.7507

The weight estimating relationship for instruments with design gross weight is $W_{10} = 42.106 + .00503W_g$, with an r^2 of 0.7313.

Fuel quantity was also a fairly reliable estimator, resulting in the following equation: $W_{10} = 48.230 + .181G$. The r^2 for this equation is 0.7253. Due to high covariance between the three estimators, ranging from 0.84 to 0.93, multiple regressions incorporating two or more explanatory variables did not improve the fit significantly.

The instrument system WER is shown graphically in Figure 4.12, together with the data from which it was derived.

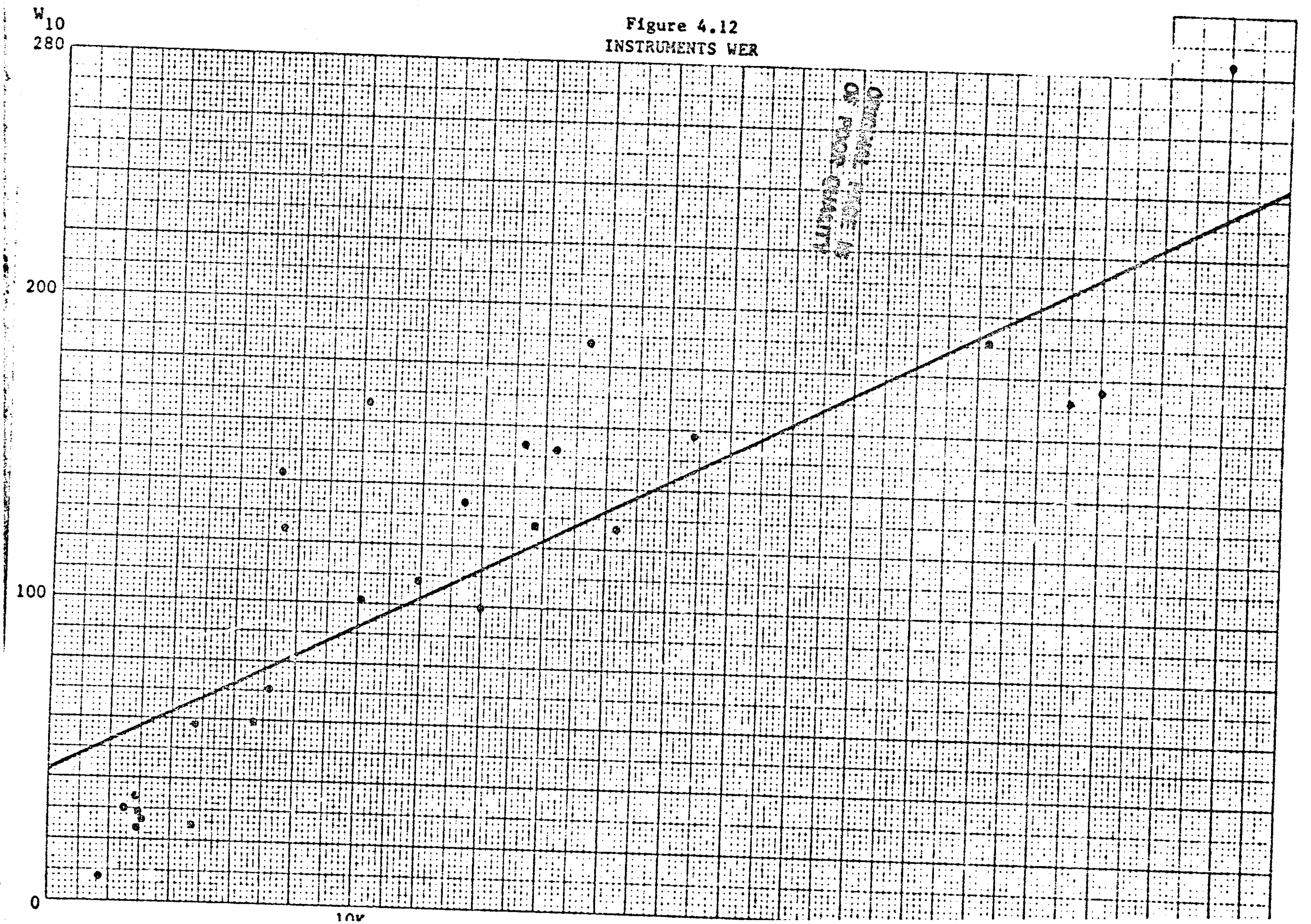
Table 4.11

INSTRUMENT SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	INSTRUMENTS W_{10}	%MEW	ENGINE HORSEPOWER HP_e	FUEL QUANTITY G	HYDRAULIC W_{11}	POWER PLANT W_{7A}
269A	8	0.8	180			336
OH-6A	30	2.5	250	62		192
TH-57A	29	1.9	317	76		194
OH-58A	27	1.7	317	73		165
OH-23G	34	1.8	305	46		551
OH-13S	24	1.2	260			588
BO105	25	1.1	600	154		348
286	58	1.9	550	82	38	369
UH-1H	59	1.1	1,103	211	33	683
H-52A	124	2.2	1,050	325	43	360
UH-19D	70	1.2	800	175	47	1,244
UH-2B	142	2.4	1,250		42	635
AH-16C	101	1.5	2,050		110	835
UH-2D	166	2.2	2,500	276	52	805
YAH-64	99	1.3	3,000	353	96	1,089
CH-34A	108	1.4	1,525	263	26	1,737
CH-21C	134	1.5	1,425	300	62	1,809
YUH-63	127	1.3	3,000	343	162	1,093
YUH-61A	153	1.6	3,000	352		831
YUH-60A	152	1.5	3,036	343	87	862
* SH-3A	368	3.2	2,500		46	701
S-67	187	1.6	3,000		40	941
AH-56A	127	1.1	3,925	438	86	969
CH-46F	158	1.2	2,600	380	168	951
CH-47A	172	1.0	4,400	620	212	1,342
CH-54A	284	1.5	9,600	1,342	168	2,185
CH-37A	191	0.9	4,200	410	129	5,516
YH-16A	176	0.8	3,600	700	224	3,706
* CH-53A	395	1.7	5,700	638	132	1,762
347	195	0.8	7,500	1,200	176	1,741

* Not used in developing WER.

Figure 4.12
INSTRUMENTS WER



Avionics System Description

The avionics system is separated into four subsystems. They are described in the following paragraphs.

Integrated Flight Guidance and Controls Subsystem

The integrated flight guidance and controls subsystem includes the autopilot unit, the flight director unit, the gyrocompass unit, the attitude and heading reference unit, and the inertial navigation unit. These units are interdependent and may be either separate, interconnected units or one, integrated functional unit. All indicators, servomechanisms, and associated circuitry, supports and attachments related to the integrated flight guidance and controls subsystem are also included. Although usually colocated with this subsystem, the auto-throttle/thrust management unit is part of the propulsion system because it functions to control the engine.

Communication Subsystem

The communication subsystem is separated into internal and external units. The internal communication unit includes the interphone system, the public address system, and the multiplex (MUX) system. The external communication unit includes the transceiver equipment which is used for aircraft-to-aircraft or aircraft-to-ground communications.

Navigation Subsystem

The navigation subsystem includes all radar equipment, the automatic direction finding (ADF) unit, the distance measuring equipment (DME) unit, the doppler unit, the navigation computer units, the station-keeping unit, the tactical air navigation (TACAN) unit, the variable omnirange (VOR) unit, the marker beacon unit, the instrument landing system (ILS), the collision avoidance unit (CAS), the airport traffic control (ATC) unit, the radio altimeter unit, the glide slope indicator, and the radar beacon unit. All of the navigation units, indicators, antennae, associated circuitry and antenna coaxial cable, and the units' supports and attachments related to the navigation subsystem are included.

Miscellaneous Equipment Subsystem

The miscellaneous equipment subsystem includes the flight, voice and crash recorder unit, the aircraft integrated data (AID)/malfunction detection analysis and recording (MADAR) unit, the weight and balance unit (if installed), and the equipment rack structure and mounting hardware and circuitry.

Weight Estimating Relationship

Avionics system weights and related characteristics are presented in Table 4.12.

Design gross weight and range* (in miles) are significant variables for estimating the weight of avionics systems. The WERs developed for avionics are:

Equation	r^2	Notes
$W_{14} = 301.770 + .0231W_g - .687R$	0.8923	Navy Trans. & Cargo
$W_{14} = -20.814 + .00739W_g + .585R$	0.9177	Army Trans. inc. UTTAS
$W_{14} = -59.041 + .0175W_g + .348R$	0.9761	Other

Avionics weights were divided into three broad mission/service categories (Navy transport and cargo, Army transport including UTTAS and all other) to improve correlation.

In the first WER, the negative coefficient for range (R) arises from the dominance of the design gross weight variable (its r^2 in a simple regression with W_{14} is 0.8246 while the r^2 with range is only 0.0748). The presence of covariance ($r^2 = 0.2938$) further weakens the range variable.

* Ranges have been adjusted to conform to the best estimates of maximum range with no reserves; this was done because of the lack of statistical uniformity. For example, a given range, assuming 10 percent fuel reserves, is adjusted upward accordingly. Therefore, ranges should be accurate to within 5 percent.

Table 4.12

AVIONICS SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

	MODEL	AVIONICS W_{14}	%MEW	MISSION	DESIGN GROSS WEIGHT W_g	RANGE R
	269A	11	1.1	-	1,600	204
	OH-6A	113	9.4	Army LOH	2,400	380
	TH-57A	53	3.5	Navy	2,900	313
	OH-58A	106	6.9	Army LOH	3,000	305
	OH-23G	98	5.1	Army	2,800	225
	OH-13S	91	4.7	Army	2,850	198
	BO105			Civilian	4,630	
*	286	20	0.7	Civilian	4,700	
	UH-1H	246	4.7	Army/Air Force	6,600	318
*	H-52A	427	7.6	Coast Guard	7,500	
*	UH-19D	110	1.9	Army/Air Force	7,100	
*	UH-2B	318	5.4	Navy Seasprite	7,378	
*	AH-16C	283	4.1	Army	10,000	
	UH-2D	362	4.7	Navy	10,187	422
	YAH-64	303	3.9	Army (AAH)	13,950	359
*	CH-34A	269	3.4	Army Trans.	11,867	
	CH-21C	247	2.7	Air Force	13,300	230
	YUH-63	308	3.2	Army (AAH)	15,645	245
	YUH-61A	456	4.6	Army (UTTAS)	15,313	551
	YUH-60A	456	4.6	Army (UTTAS)	16,250	691
*	SH-3A	1,273	11.1	Navy (ASW)	18,064	625
*	S-67	737	6.3	Attack - Proto.	17,300	445
*	AH-56A	650	5.4	Army	18,300	
	CH-46F	645	4.8	Navy Cargo	20,800	246
	CH-47A	303	1.7	Army Trans.	33,000	225
	CH-54A	435	2.3	Army Lift	38,000	230
*	CH-37A	269	1.3	Army	30,342	
*	YH-16A	303	1.3	-	34,000	
	CH-53A	659	2.9	Marine Trans.	33,500	540
*	347	371	1.5	-	42,500	

* Not used in developing WER.

Neither variable predominates in the second WER. The r^2s in simple regressions with design gross weight and range are 0.2955 and 0.4448, respecively. Covariance is negative ($r = -0.1960$) and weak ($r^2 = 0.0384$), strengthening the multiple r^2.

As in the first WER, the final one is dominated by design gross weight. (Simple r^2s are 0.9318 and 0.0472 for design gross weight and range, respectively).

The surprising result of design gross weight being more powerful then range is due to the categorical divisions, which largely "normalize" the range variable. A single equation for all models shows range to be slightly more powerful than design gross weight, but both are low predictors, resulting in an overall multiple r^2 of 0.6316.

In view of constantly changing technology, this weight estimating relationship should be viewed with great caution. Rapidly increasing sophistication in avionics packages could have unpredictable consequences for weight estimation. In addition, increased avionics "requirements" might result in heavier systems, although higher levels of technology could offset any increase in weight.

Because the avionics WER uses two independent variables, it is not presented graphically.

H. HYDRAULIC SYSTEM

Hydraulic System Description

The hydraulic system on helicopters is required primarily to provide hydraulic power to the hydraulic flight controls. In a few cases, hydraulic power is also used for landing gear retraction and to power cargo handling accessories. The hydraulic system includes: pumps, reservoirs, accumulators, filters, regulators, valves, manifolds, plumbing, fluid, and supports and mounting hardware.

Weight Estimating Relationship

Weights and design characteristics relevant to the hydraulic system are presented in Table 4.13.

Several independent variables were considered in deriving a WEP for the hydraulic system. Design gross weight proved to be the most reliable estimator, as indicated below:

Equation	r^2
$W_{11} = 15.890 + .00446W_g$	0.6574

Although flight controls weight is perhaps the more logical estimator on account of the functional relationship between the two systems, the equation derived with flight controls weight, $W_{11} = 19.508 + .0110W_{fc}$, has an r^2 of only 0.5760.

Due to high covariance between design gross weight and flight controls weight, a multiple regression equation of hydraulic weight on both independent variables adds nothing to the r^2. Nevertheless, a robust combined weight equation was derived: $W_{8+11} = 59.692 + .390W_g$. Its r^2 is 0.9341, which is comparable to the correlation coefficient for the flight controls equation.

As in the case of flight controls, wings and tandem rotors, even though they might be regarded as aids in flight control, are not a determining factor for hydraulic weight. Also, none of the weight or performance factors related

Table 4.13

HYDRAULIC SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	HYDRAULIC W_{11}	%MEW	DESIGN GROSS WEIGHT W_g	POWER-PLANT W_{7A}	FLIGHT CONTROLS W_8
269A			1,600	336	51
OH-6A			2,400	192	65
TH-57A			2,900	194	133
OH-58A			3,000	165	125
OH-23G			2,800	551	108
OH-13S			2.850	588	153
BO105			4,630	348	189
286	38	1.3	4,700	369	327
UH-1H	33	0.6	6,600	683	357
H-52A	43	0.8	7,500	360	353
UH-19D	47	0.8	7,100	1,244	164
UH-2B	42	0.7	7,378	635	301
AH-16C	110	0.2	10,000	835	469
UH-2D	52	0.7	10,187	805	300
YAH-64	96	1.2	13,950	1,089	419
CH-34A	26	0.3	11,867	1,737	378
CH-21C	62	0.7	13,300	1,809	561
YUH-63	162	1.7	15,645	1,093	596
YUH-61A			15,313	831	721
YUH-60A	87	0.9	16,250	862	694
SH-3A	46	0.4	18,064	701	654
S-67	40	0.3	17,300	941	780
AH-56A	86	0.7	18,300	969	1,021
CH-46F	168	1.3	20,800	951	828
CH-47A	212	1.2	33,000	1,342	1,212
CH-54A	168	0.9	38,000	2,185	1,161
CH-37A	129	0.6	30,342	5,516	965
YH-16A	224	1.0	34,000	3,706	1,239
CH-53A	132	0.6	33,500	1,762	1,168
347	176	0.7	42,500	1,741	1,921

to the powerplant (i.e., powerplant weight or engine horsepower) are statistically significant as predictors of hydraulic system weight.

The hydraulic system WER is presented graphically in Figure 4.13, together with the data from which it was derived.

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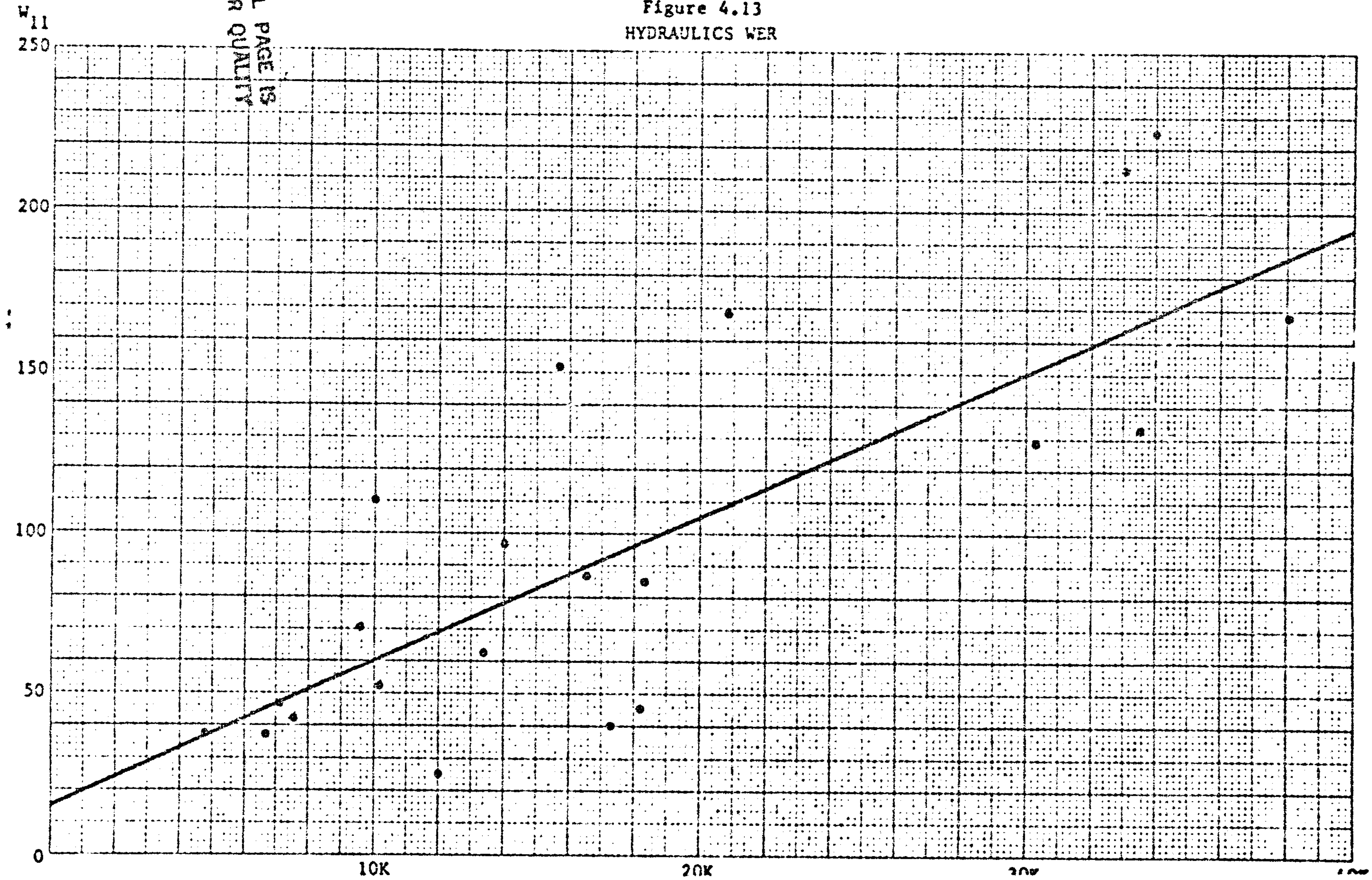
Figure 4.13
HYDRAULICS WER



I. ELECTRICAL SYSTEM

Electrical System Description

The electrical system supplies power to a variety of helicopter operating components, including, among others: lights, avionics, instruments, passenger and cargo doors, cargo hoist, and environmental control system.

The electrical system consists of the AC power system, the DC power system and the lighting system. The AC system includes power generating equipment, while the DC power system includes converters and batteries, and both include the necessary controls, wiring, cables, fittings and supports to distribute the electrical power from the power source to the electrical power center.

The lighting system includes all interior and exterior lights, together with the switches, associated circuitry from the electric power center, and support hardware.

The wiring and circuitry leading from the electric power center to the various components which use electricity are included with the respective systems.

Weight Estimating Relationship

Weights and related design criteria for the electrical system are provided in Table 4.14.

Total body surface area is the most reliable estimator of electrical system weight. As the graph in Figure 4.14 shows, the ratio of electrical system weight to body surface area decreases as they increase, implying a logarithmic relationship, which indeed increases the r^2 significantly. Both the logarithmic and the linear versions are presented below:

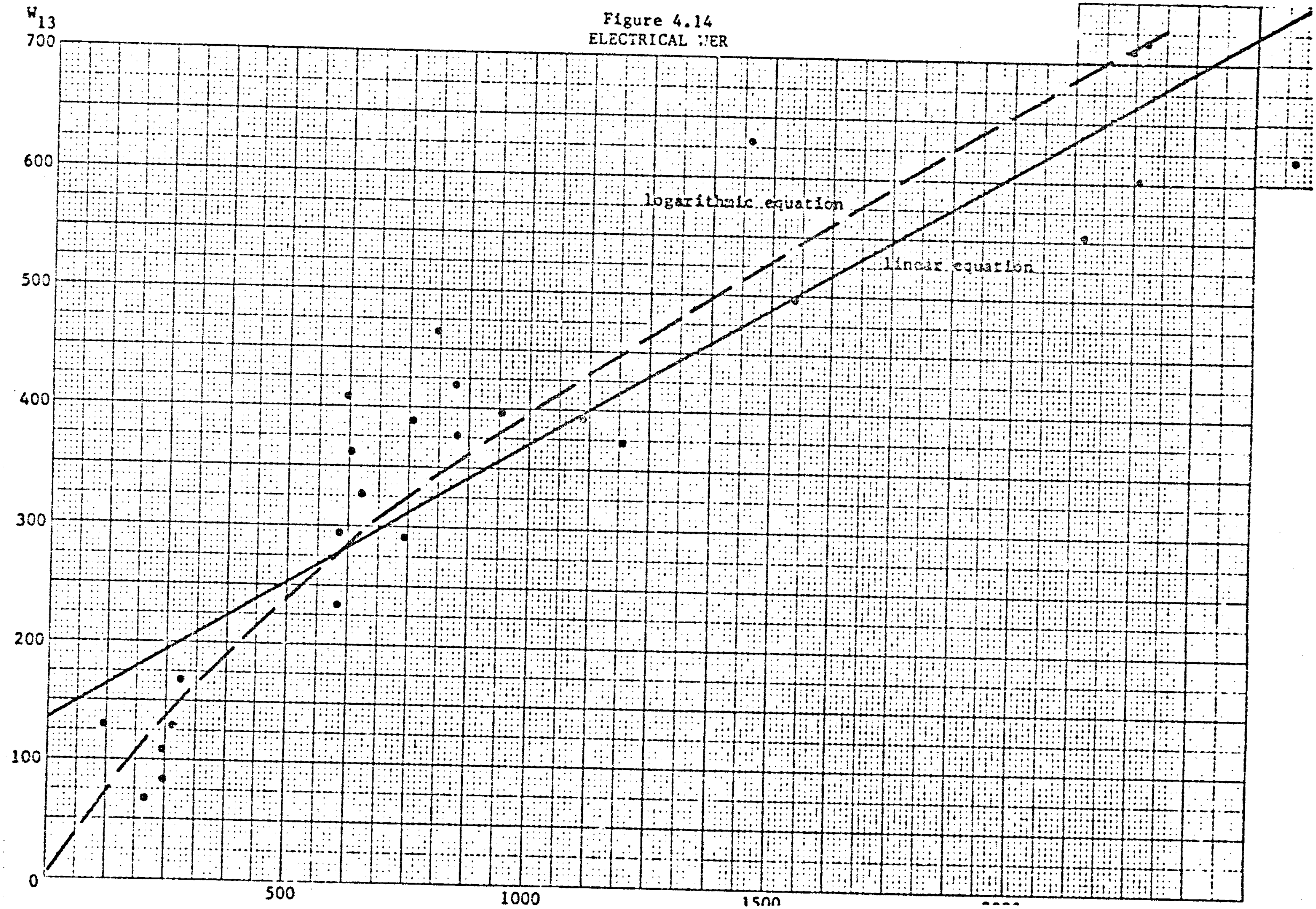
Equation	r^2
$\ln W_{13} = .903 + .733 \ln S_b$	0.8547
$W_{13} = 139.947 + .234 S_b$	0.8160

Table 4.14

ELECTRICAL SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	ELECTRICAL W_{13}	%MEW	BODY SURFACE AREA S_b	NUMBER OF PASSENGERS N_p
* 269A	59	6.0		1
OH-6A	68	5.7	205	2
TH-57A	110	7.2	244	
OH-58A	85	5.5	247	
* OH-23G	111	5.8		1
OH-13S	130	6.7	121	1
BO105	168	7.2	277	
286	130	4.4	262	3
UH-1H	360	6.9	626	11
H-52A	419	7.5	849	
UH-19D	327	5.6	640	3
UH-2B	233	3.9	609	4
* AH-16C	400	5.8	469	
UH-2D	293	3.8	738	1
YAH-64	294	3.7	606	
CH-34A	327	4.2	817	14
* CH-21C	342	3.7	1,180	
YUH-63	409	4.2	623	
YUH-61A	389	4.0	757	11
YUH-60A	464	4.5	805	11
SH-3A	391	3.4	1,112	16
S-67	397	3.4	943	
AH-56A	377	3.1	847	
CH-46F	654	4.9	1,452	22
CH-47A	555	3.1	2,150	32
CH-54A	472	2.5	1,199	
CH-37A	497	2.3	1,553	
YH-16A	708	3.1	2,300	
CH-53A	601	2.6	2,262	37
347	617	2.5	2,587	37
Others				
CH53E	704	2.3	2,242	37

* Not used in developing WER.



W_{13}
Figure 4.14
ELECTRICAL WER
logarithmic equation
linear equation
700
600
500
400
300
200
100
0
500
1000
1500

Passenger capacity was also investigated but was a far less reliable estimator, with an r^2 of only 0.63.

Finally, design gross weight was analyzed as a possible explanatory variable. A linear equation was found to have an r^2 of only 0.74, although its logarithmic version yielded an r^2 of 0.83. Alternative electrical system WERs which employ the design gross weight variable are $W_{13} = 145.813 + .0133W_g$ and $\ln W_{13} = -.5385 + .6728 \ln W_g$. The low r^2 for the linear version is primarily due to the wide variance from the trend line for models over 20,000 pounds. As this variance for heavier helicopters is far less apparent in the equation presented above, using linear body surface area, its correlation coefficient is much higher and it is clearly preferred.

The preferred electrical system WERs are presented graphically in Figure 4.14, together with the data from which they were derived.

J. FURNISHINGS AND EQUIPMENT SYSTEM

Furnishings and Equipment System Description

Furnishings and equipment include a variety of items in the cockpit and the passenger and/or cargo compartment. In the cockpit, this category includes all instrument and console panels, seats, insulation, lining, crew oxygen system, and cockpit door and partitions.

In the passenger and/or cargo compartment, this category includes seats, floor covering, insulation, side panels, ceiling structure, hatrack or baggage containers, and passenger comfort items such as galley or lavatory installations.

Miscellaneous items include the engine and cabin fire extinguisher systems, fire warning system, exterior finish, and emergency equipment (i.e., first aid kit and fire ax). Cargo loading equipment is also a part of this system.

Weight Estimating Relationship

Weights and related design information for helicopter furnishings and equipment are presented in Table 4.15.

Two explanatory variables, the sum of crew and passengers and the total surface body area, are highly significant in estimating the weight of the helicopter furnishings. The following WER was obtained based on them:

Equation	r^2
$W_{15} = -8.106 + .176S_b + 20.456(N_p+N_c)$	0.9034

Single regressions for each variable provide the following results: $W_{15} = 75.356 + 28.528(N_p+N_c)$ and $W_{15} = -41.620 + .444S_b$. These equations have r^2s of 0.8927 and 0.7081, respectively. The highest r^2 is, however, obtained by including both variables, as indicated above.*

* Contemporary helicopter designs typically include material to reduce vibration. The weight of absorption material added is about 2.5 percent of design gross weight. Therefore, another variable ($0.025W_g$) should be added to this WER for estimating the furnishings and equipment system weight in modern helicopters.

Table 4.15

FURNISHINGS AND EQUIPMENT SYSTEM WEIGHT, PERFORMANCE AND DESIGN DATA

MODEL	FURNISH & EQUIP W_{15}	%MEW	NUMBER OF PASSENGERS N_p	NUMBER OF CREW N_c	BODY SURFACE AREA S_b
* 269A	33	3.4	1	2	
OH-6A	58	4.8	2	1	205
TH-57A	64	4.2		3	244
OH-58A	42	2.7		2	247
* OH-23G	32	1.7	1	1	
OH-13S	30	1.6	1	1	121
BO105	47	2.0		2	277
286	84	2.8	3	2	262
UH-1H	408	7.8	11	2	626
H-52A	216	3.9		3	849
UH-19D	205	3.5	3	1	640
UH-2B	131	2.2	4	2	609
AH-16C	130	1.9		2	469
UH-2D	166	2.2	1	3	738
YAH-64	185	2.4		2	606
CH-34A	189	2.4	14	2	817
* CH-21C	258	2.8			1,180
YUH-63	202	2.1		2	623
YUH-61A	650	6.6	11	3	757
YUH-60A	675	6.6	11	3	805
SH-3A	400	3.5	16	2	1,112
S-67	230	2.0		2	943
AH-56A	274	2.3		2	847
CH-46F	854	6.4	22	3	1,452
CH-47A	866	4.9	32	3	2,150
CH-54A	218	1.1		2	1,199
* CH-37A	810	3.8			1,553
YH-16A	425	1.9		3	2,300
CH-53A	1,289	5.6	37	3	2,262
347	1,337	5.4	37	3	2,587

* Not used in developing WER.

The principal reason for combining body surface area and the number of passengers and crew in a multiple regression equation is the difficulty in classifying models as "cargo" and "non-cargo" helicopters. Previous attempts to derive separate weight estimating relationships by type indicate that the number of passengers plus crew members is the best estimator for the strictly non-cargo models and that body surface area is the best for the strictly cargo models. The covariance between these two variables is only 0.5660, allowing for a multiple regression with a high r^2.

A problem experienced in deriving this equation was the accurate determination of the number of passengers and crew for each model. Available data often differed significantly according to the available source documentation, including manufacturers' weight statements, armed service and government agency compilations, and other outside sources (e.g., Jane's All the World's Aircraft). The passenger and crew statistics provided in the accompanying table are those which were used. They represent median estimates from these sources for passenger models. For dual-function helicopters, the figures represent estimates of the "most likely" number of passengers and crew in an all-passenger configuration.

In summary, the final multiple regression equation eliminates the need to derive different relationships for different model types and, thereby, eliminates the need to dichotomize dual-function models arbitrarily. It also reduces the dependence on the differing passenger and crew statistics from more than one source and results in a significantly higher correlation.

Because this WER has two independent variables, a graphic presentation is not provided.

K. LOAD AND HANDLING SYSTEM

Load and Handling System Description

The load and handling system consists of loading and handling gear, including provisions for jacking, hoisting and mooring, and ballast.

Weight Estimating Relationship

Load and handling system weights and related design characteristics are presented in Table 4.16.

The weight estimating relationship developed for the load and handling system is:

Equation	r^2
$W_{18} = -71.875 + .111S_b + 3.489(N_p+N_c)$	0.7704

As indicated, body surface area and the sum of passengers and crew are significant estimators. Simple regression equations give the following results: $W_{18} = -77.353 + .157S_b$ and $W_{18} = 19.962 + 7.708(N_p+N_c)$. These equations have r^2s of 0.6910 and 0.5764, respectively. Covariance is only 0.4328, allowing for inclusion of both variables, which results in an improved multiple correlation.

One should not be surprised by the strong positive relationship between load and handling system weight and the number of passengers and crew in the second simple regression equation, even though the system relates to cargo: For dual-function models, the passenger statistics reflect what the craft is <u>capable</u> of carrying in an "all passenger" configuration, i.e., the bigger its passenger (troop) capacity, the larger will be its potential cargo capacity. In fact, the very large models are designed to carry troups and/or military hardware, the relative quantities of which often vary from one mission to another.

Because the load and handling system WER uses two independent variables, it is not presented graphically.

Table 4.16

LOAD AND HANDLING SYSTEM
WEIGHT, PERFORMANCE AND DESIGN DATA

	MODEL	LOAD & HANDLING W_{18}	%MEW	NUMBER OF PASSENGERS N_p	NUMBER OF CREW N_c	BODY SURFACE AREA S_b
	269A			1	2	
	OH-6A			2	1	205
	TH-57A				3	244
	OH-58A				2	247
	OH-23G			1	1	
	OH-13S			1	1	121
	BO105				2	277
	286			3	2	262
	UH-1H			11	2	626
	H-52A	89	1.6		3	849
	UH-19D			3	1	640
	UH-2B	6	0.1	4	2	609
	AH-16C				2	469
*	UH-2D	131	1.7	1	3	738
	YAH-64				2	606
	CH-34A	3	†	14	2	817
*	CH-21C	45	0.5			1,180
	YUH-63				2	623
	YUH-61A	39	0.4	11	3	757
	YUH-60A	80	0.8	11	3	805
	SH-3A	56	0.5	16	2	1,112
	S-67	13	0.1		2	943
	AH-56A				2	847
	CH-46F	196	1.5	22	3	1,452
	CH-47A	258	1.5	32	3	2,150
	CH-54A	184	1.0		2	1,199
*	CH-37A	12	0.1			1,553
	YH-16A	137	0.6		3	2,300
	CH-53A	439	1.9	37	3	2,262
	347	302	1.2	37	3	2,587

* Not used in developing WER.

† Less than 0.05%.

SECTION 5

DETAILED SYSTEM COST ANALYSES

This section provides a detailed discussion of each recurring production cost estimating relationship (CER) which was presented in Table 3.1. Specifically, the cost data used to develop the CERs are discussed, assumptions made and methodology used in developing the CERs are presented and the perceived validity of the CERs is indicated. Since this study followed the SAI report[1] on transport aircraft systems costs, references will frequently be made to it whenever it could be helpful in discussing similarities and differences which influence the cost of both aircraft types.

Descriptions of each individual system are provided with the discussion of that system in Section 4, Detailed System Weight Analyses. A summary of system descriptions is also provided in Appendix B.

A. WING, TAIL, BODY AND NACELLE SYSTEMS

The structural systems (wing, tail, body and nacelle) are discussed together because they have similar designs and use similar materials and methods of fabrication. Also, the data upon which each system CER was based were derived from the same source.

Discussion of Wing, Tail, Body and Nacelle Systems Cost Data and CER Development

Detailed cost data for helicopter airframe structures were not readily available. This is because the structure is generally produced by the manufacturer and reported costs typically include in-house assembly costs as well as in-house production and subcontractor costs. However, one case was identified in which the entire airframe structure is being provided by a subcontractor. Thus, detailed cost estimates developed by the subcontractor's design team served as the basis for the CERs developed for helicopter airframe structure. However, since the data provided were in terms of labor hours and material costs for a production of much more than 100 units, the following assumptions and adjustments were made to estimate the CAC_{100} cost per pound in \$FY77:

- A labor rate of \$35 per hour was used, based on information from other aerospace industry sources.
- An 82 percent learning curve was assumed, based on conversations with the subcontractor, in estimating the CAC_{100}.
- The total estimated material cost was divided by its total estimated weight and the result was converted from \$FY72 to \$FY77 by use of DoD inflation factors. The result was \$13 per pound for the structural material.

Costs per pound of about \$120 for the wing, \$90 for the tail, \$80 for the body, and \$110 for the nacelle were obtained. These were within the range indicated in other sources. To develop CERs, these points were plotted and a 90 percent weight scaling curve* was assumed based on transport aircraft data and discussion with helicopter industry personnel, which confirmed the validity of these values.

The helicopter airframe structure CERs are:

System	Equation
Wing	$C_1 = 1019W_1^{0.848}\ Q^{-0.286}$
Tail	$C_{3B} = 759W_{3B}^{0.848}\ Q^{-0.286}$
Body	$C_4 = 860W_4^{0.848}\ Q^{-0.286}$
Nacelle	$C_6 = 893W_6^{0.848}\ Q^{-0.286}$

The wing, tail and nacelle structure CERs are presented in Figure 5.1. The body CER is presented in Figure 5.2.

As noted, the tail rotor is considered to be part of the tail system. Detailed cost data were not available for it; however, since analysis indicated that it was similar to, but smaller than, the main rotor, the following CER was assumed:

System	Equation
Tail Rotor	$C_{3A} = 102W_{3A}\ Q^{-0.0740}$

The tail rotor CER is presented in Figure 5.3.

The figures represent cumulative average costs for 100 units in 1977 dollars and include only in-house production costs and subcontractor costs, as discussed in Section 3.

Perceived Validity of Wing, Tail, Body and Nacelle Systems CERs

Since each of these structure CERs was based on detailed subcontractor cost estimates and the subcontractor discussed the bases and methodology used in preparing these estimates, a confidence value of 8 was assigned to

* This curve indicates that cost per pound decreases as weight increases as a reflection of the relatively easier and less extensive fabrication techniques required for larger structures. Weight scaling curves are similar to learning curves, which were discussed in Section 3.

Figure 5.1

WING, TAIL AND NACELLE STRUCTURE CERs

(Thousands of $FY77)

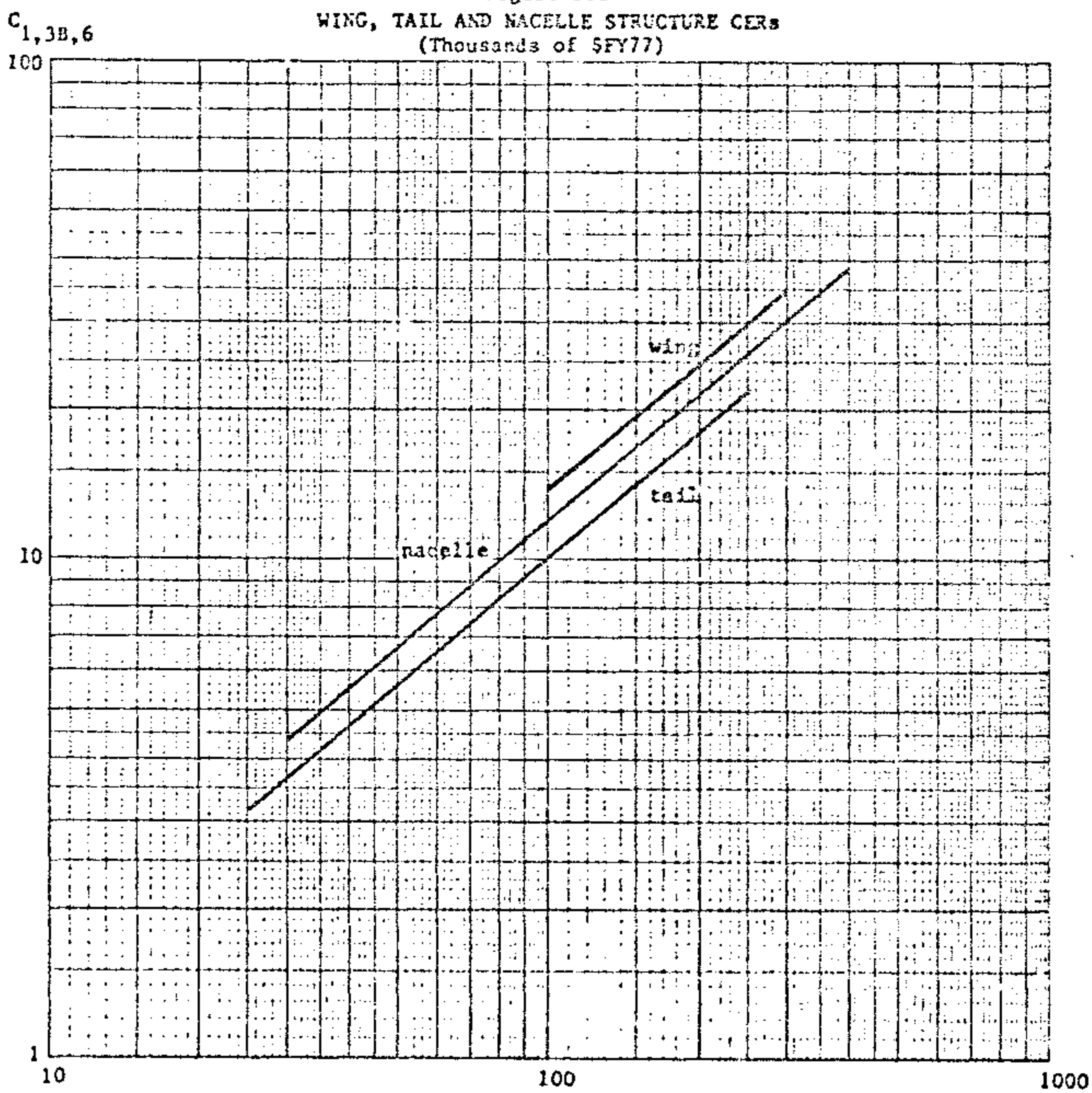


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Figure 5.2
BODY CER
(Thousands of $FY77)

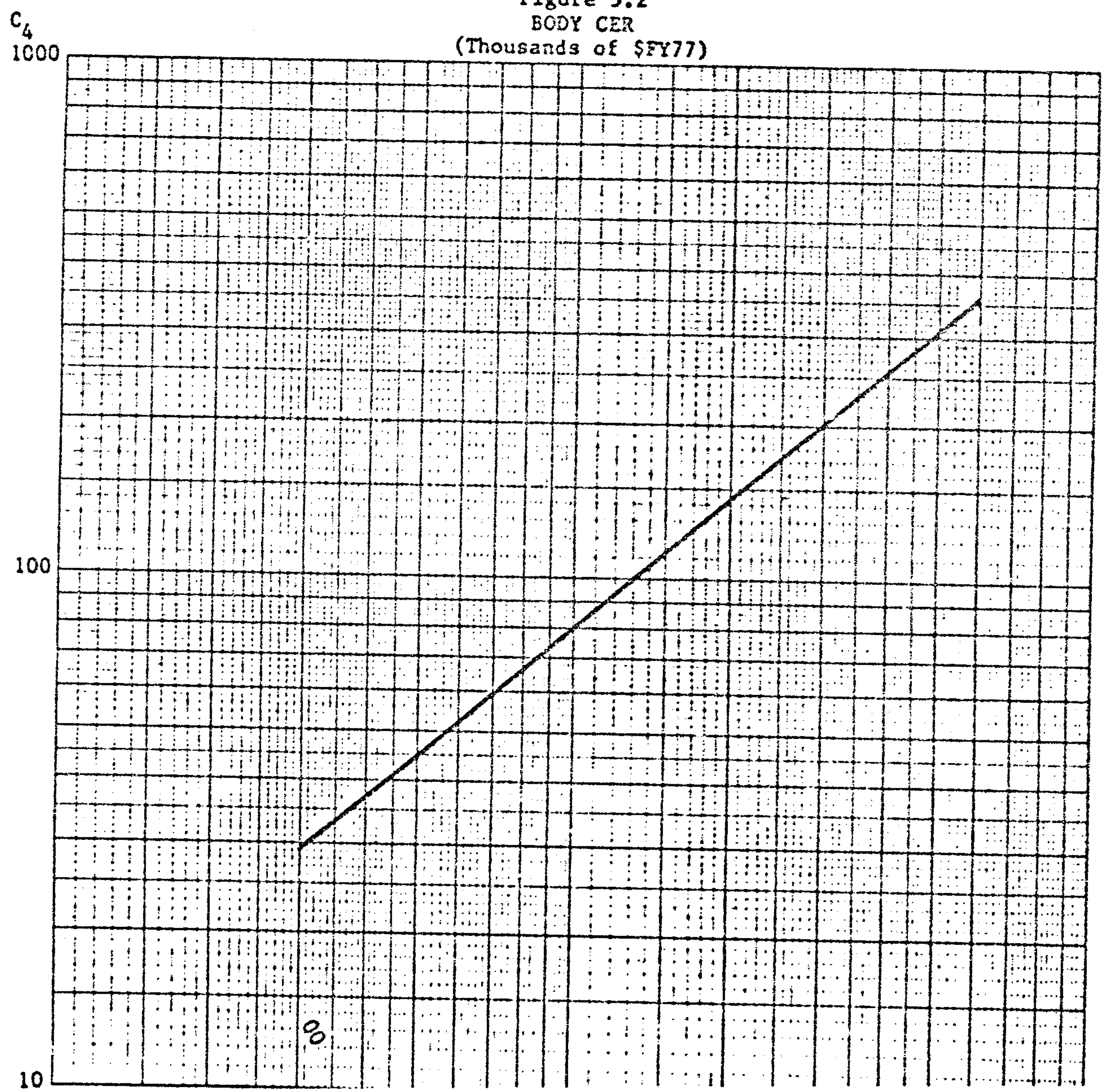
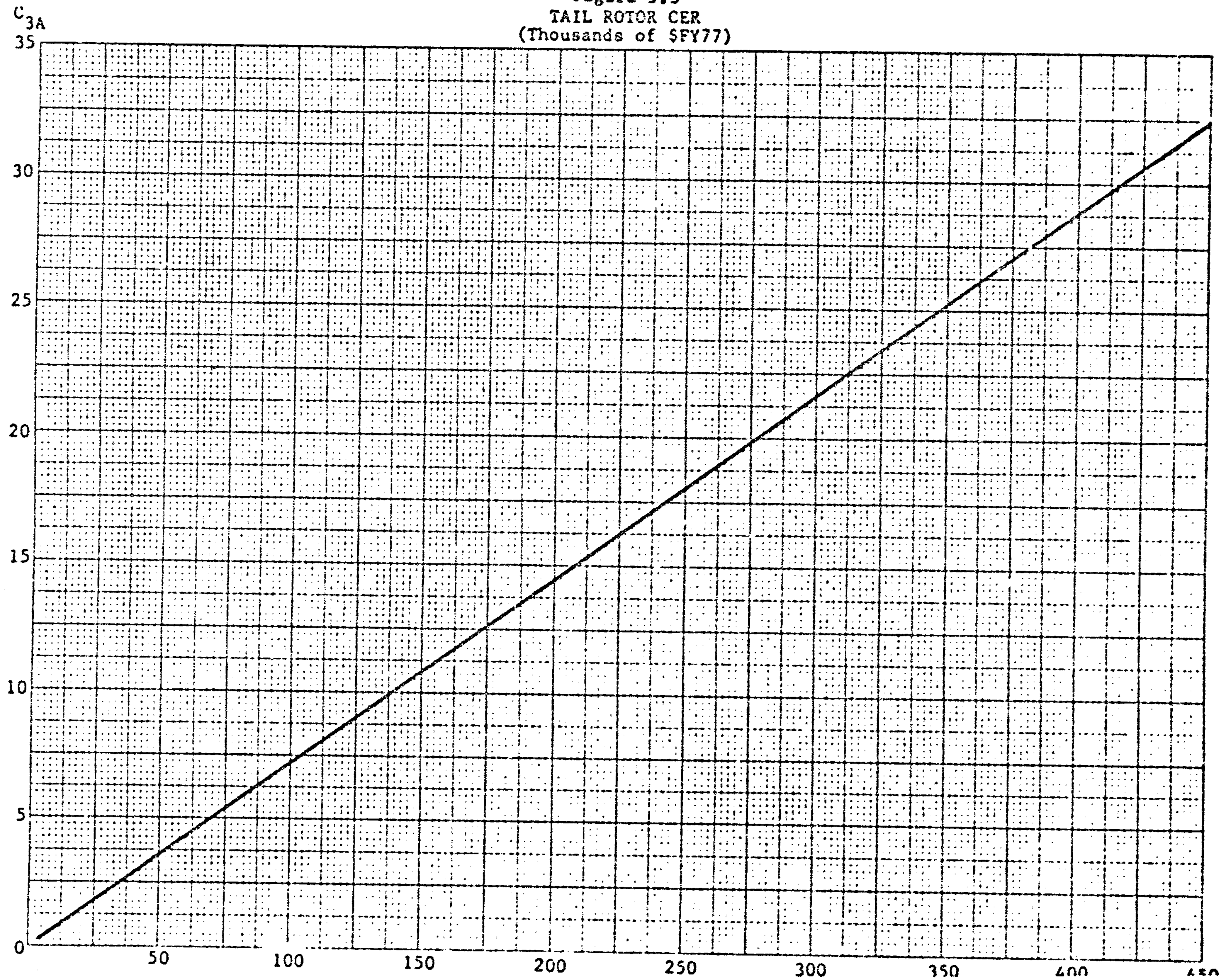


Figure 5.3
TAIL ROTOR CER
(Thousands of $FY77)



each of them in accordance with Table 3.3. The tail rotor CER was developed based on the assumption of its similarity to the main rotor and, therefore, a lower value of S was assigned to it.

Emerging Technologies

The use of composites is now being implemented for selected items and in a limited manner for some current helicopter models. These materials offer significant weight savings at a higher cost. The material cost is currently about three times that of normal (aluminum) structural materials (about \$40 to \$50 per pound, compared to about \$13 per pound). Further, fabrication costs are currently about double the cost of aluminum structure. It is anticipated that both material and fabrication costs will decline substantially when wide scale production is implemented, although it is impossible to define "substantially" in a financial sense at this time.

B. ROTOR SYSTEM

Discussion of Rotor System Cost Data and CER Development

Cost data were obtained for rotors for eight different models of military helicopters.(2) Although data were also available for different types of a particular model, they were not included in the final analysis in order to avoid possible bias in favor of a particular design theory or manufacturing practice. When helicopters with twin rotors were included, regressions were performed for cases where the total cost and weight were used and where one half of the total cost and weight were used. There was no significant difference between the two results. The following CER was determined:

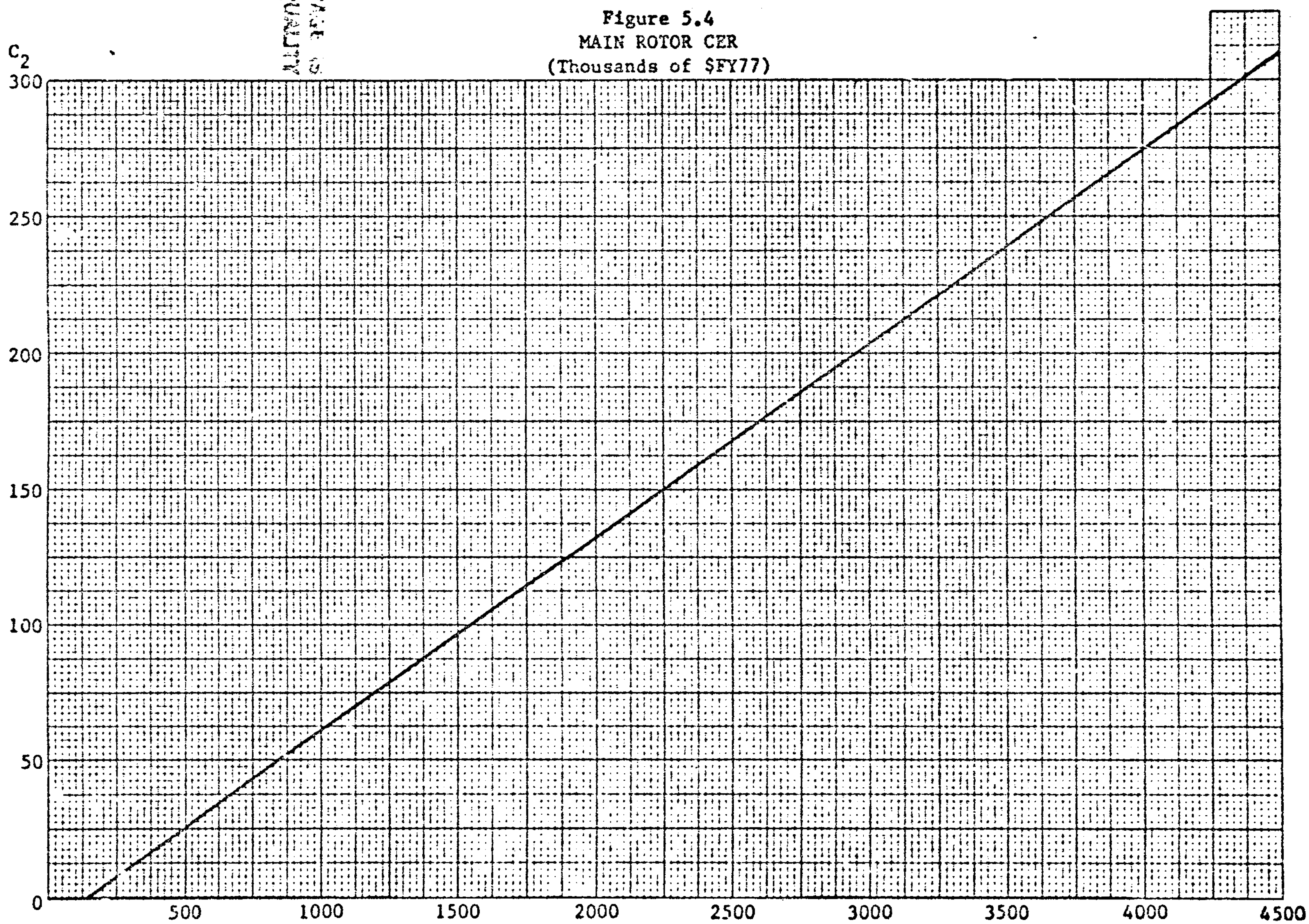
Equation	r^2
$C_2 = -12{,}938 + 101W_2Q^{-0.0740}$	0.9448

The rotor cost estimating relationship is presented in Figure 5.4. This is the cumulative average cost for 100 units in fiscal year 1977 dollars and includes only in-house production and subcontractor costs, as discussed in Section 3. The weight range shown conforms with that of the data base.

Perceived Validity of Rotor System CER

As indicated by the r^2 of 0.9448, the scatter of the data used was minimal. Further, eight diverse helicopter models were represented in the rotor data and their weights ranged from about 150 to 4,000 pounds. Since these data were also either provided or reviewed by the manufacturers, a high confidence value of 9.5 was assigned to this CER, in accordance with the criteria specified in Table 3.3.

Figure 5.4
MAIN ROTOR CER
(Thousands of $FY77)



C. ALIGHTING GEAR SYSTEM

Discussion of Alighting Gear Cost Data and CER Development

CERs were developed for each of the alighting gear types with either skids or wheels. For larger helicopters with wheels, separate CERs were developed for the structure, controls and rolling assembly. A CER which is compatible with the WER for the complete alighting gear system was also developed. Data for developing these CERs were obtained from interviews with alighting gear subcontractors and from the similar applicable cost data reported in our earlier study.(1)

The transport aircraft alighting gear subsystem cost data were used because (at the subsystem level) costs per pound are similar to those of their helicopter counterparts. However, the cost per pound for the total helicopter alighting gear system is usually less than the transport aircraft system. Since helicopter alighting gears are typically not retractable, hydraulic actuators are not required to raise and lower them and, therefore, controls (the most costly landing gear item) comprise a smaller portion of the total helicopter alighting gear system.

The following CERs were developed for wheeled helicopter alighting gears:

System	Equation
Total Wheeled Alighting Gear	$C_5 = 84W_5 Q^{-0.2176}$
Alighting Gear Structure	$C_{5A} = 362W_{5A}Q^{-0.286}$
Alighting Gear Controls	$C_{5B} = 159W_{5B}Q^{-0.0896}$
Rolling Assembly	$C_{5C} = 20W_{5C}Q^{-0.0896}$

Learning curves of 82 percent for structure and 94 percent for subcontractor or vendor items (controls and rolling assembly) are incorporated into the subsystem equations. The subsystem CERs should be used and aggregated if weight data are available at that level, as they should provide a somewhat more accurate estimate than if the total system CER is used.

For skid-fitted helicopters, the alighting gear is a structural item (as noted above), and it is generally built by the airframe manufacturer. Its cost is estimated by the following CER:

System	Equation
Total Skid Alighting Gear	$C_5 = \frac{W_5}{W_4} C_4$

Graphs of the structure, control and rolling assembly CERs are presented in Figure 5.5. This figure represents the cumulative average cost of 100 units in 1977 dollars and includes only in-house production and subcontractor costs, as discussed in Section 3.

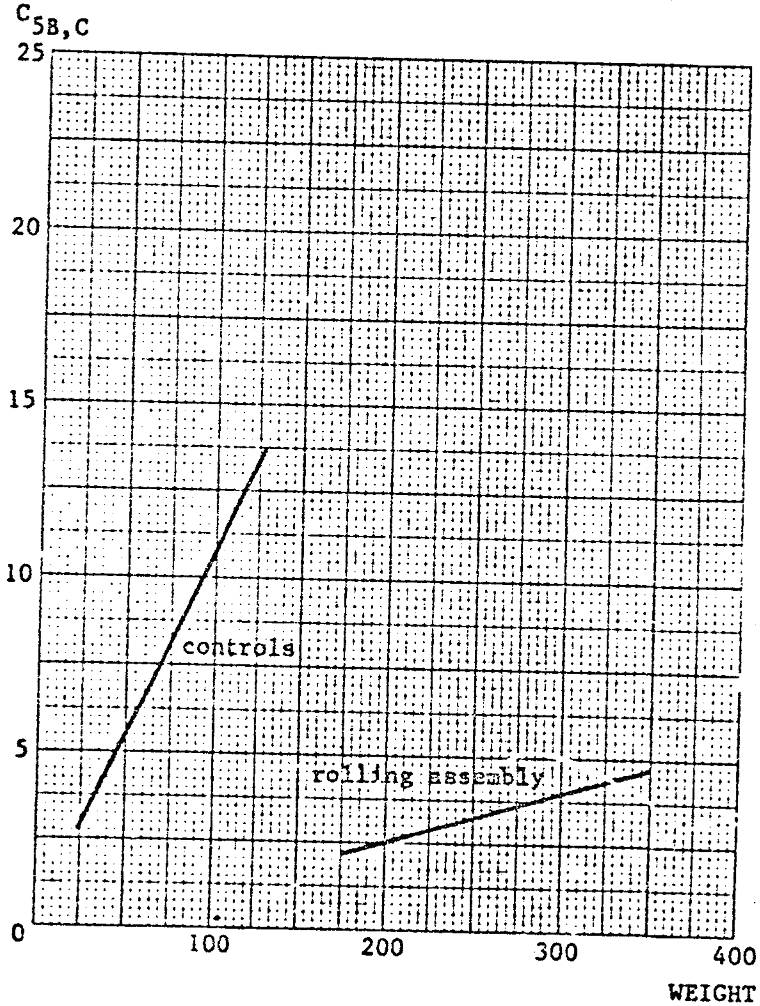
Perceived Validity of Alighting Gear System CERs

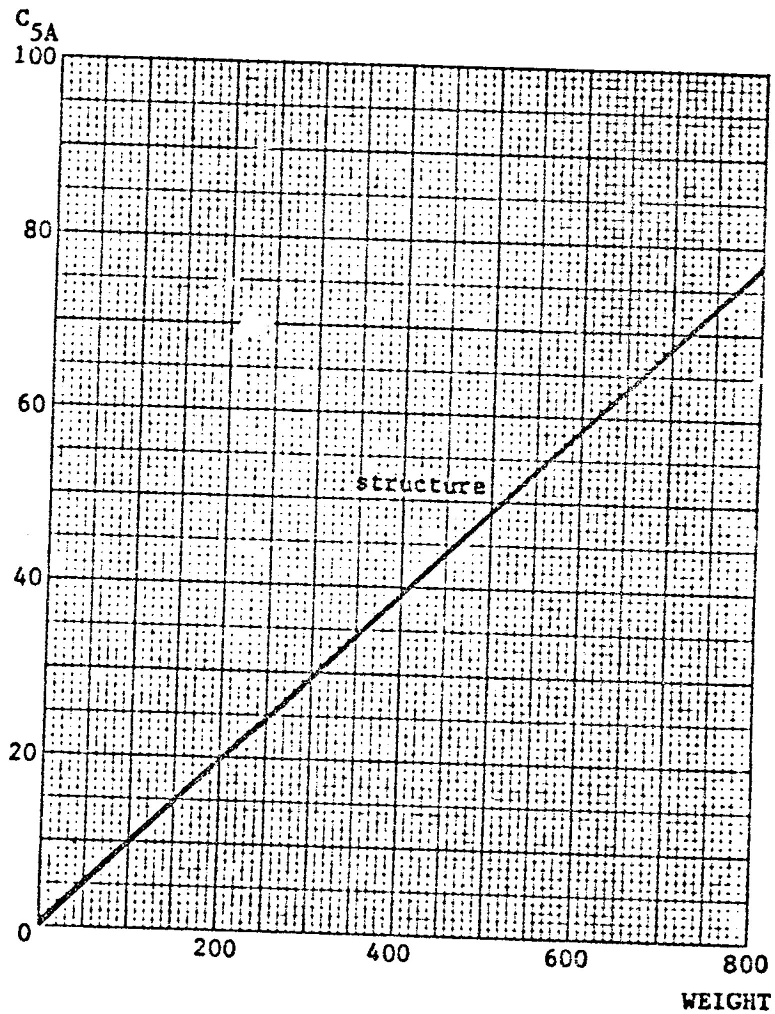
As noted, alighting gear subsystem CERs are based largely on transport aircraft data used in conjunction with helicopter alighting gear subcontractor discussions. However, especially high confidence is not warranted and a confidence value of 8 was assigned to each subsystem. Since the skid CER is based on the assumption that it costs the same per pound as the body, a confidence value of 3 was assigned to it. These confidence values are consistent with the criteria specified in Table 3.3.

Emerging Technologies

A few current and several future helicopter designs are incorporating a retractable alighting gear to improve their performance and to save energy by decreasing the wind resistance caused by fixed alighting gears. However, this feature is accomplished only by incurring a weight penalty caused by the additional controls required for retraction. Since controls are a relatively high cost item, their addition would increase the overall system cost markedly.

Figure 5.5
ALIGHTING GEAR CERs
(Thousands of $FY77)





D. PROPULSION SYSTEM

Discussion of Propulsion System Cost Data and CER Development

Regression analysis was applied to detail cost data for bare engines and drives in order to develop CERs for them. Reported costs were available for five different helicopter turbine engines found on two smaller (under 7,000 pounds MEW) and three larger (over 12,000 pounds MEW) helicopters. These costs were adjusted to represent CAC_{100} in $FY77, as discussed in Section 3. These were then correlated using dry engine weight as the independent variables. The following CER was obtained:

Subsystem	Equation	r^2	Notes
Powerplant	$C_{7A} = -17,709 + 1219W_{7A}Q^{-0.2345}$	0.8780	$W_{7A} \leq 900$ pounds

When cost was correlated with maximum shaft horsepower (HP_e), the following equation was obtained: $C_{7A} = 83,320 + 215HP_eQ^{-0.2345}$. Although the r^2 is slightly better (0.9082) than that based on weight, weight is used as the primary variable for consistency, since the improvement is minor. A learning curve of 85 percent was incorporated, as indicated by the data.

CERs were developed for drives using data from the same eight helicopter models which were used to develop the rotor CER discussed above. These data fell into two groups: Three drives were under 700 pounds and five were over 1,800 pounds. Thus, two CERs were developed, as follows:

Subsystem	Equation	r^2	Notes
Drive	$C_{7B} = -4795 + 207W_{7B}Q^{-0.0740}$	0.9980	$W_{7B} \leq 700$ pounds
Drive	$C_{7B} = -16,423 + 83W_{7B}Q^{-0.0740}$	0.9742	$W_{7B} \geq 1,800$ pounds

Since there was a potential gap between 700 and 1,800 pounds, a third regression was performed using all eight data pounts. It yielded the following CER:

Subsystem	Equation	r^2	Notes
Drive	$C_{7B} = 19,946 + 83W_{7B}Q^{-0.0740}$	0.9722	All other 7B

This equation should provide acceptable results for estimating the recurring production cost for drives between 700 and 1,800 pounds. The data indicated that very little learning was experienced for the drive and a learning curve of 95 percent was incorporated in the equation.

A detailed review of the components which comprise the fuel and other propulsion systems* indicated that they were quite similar to their transport aircraft counterparts. Therefore, the transport aircraft CERs for these subsystems were used, after adjusting them to $FY77 and removing profit and system level assembly costs. The CERs are:

System	Equation
Fuel	$C_{7C} = 56W_{7C}Q^{-0.0896}$
Other Propulsion	$C_{7D} = 145W_{7D}Q^{-0.0896}$

A 94 percent learning curve was assumed and incorporated into them.

The CER for powerplants is presented in Figure 5.6; CERs for drives are presented in Figures 5.7, 5.8 and 5.9, for fuel in Figure 5.10 and for other propulsion in Figure 5.11. These figures represent cumulative average costs for 100 units in $FY77 and include only in-house production and subcontractor costs, as discussed in Section 3.

Perceived Validity of Propulsion System CERs

Since the powerplant and drive system CERs are based on reported cost data which have been reviewed by the manufacturers, they are assigned confidence values of 8 and 9, respectively. The drive system CERs received a higher confidence value because of their higher correlation coefficients and because they were based on more data points (8 vs. 5). Since the fuel system and other propulsion system CERs were based on their indicated similarity to their transport aircraft counterparts and no data or advice from industry personnel were obtained, they were each assigned confidence values of 4, based on the criteria specified in Table 3.3.

* Other propulsion items include: starter, air inductor, exhaust and cooling items, lubrication systems, and engine controls as well as installation hardware and residual fluids.

Figure 5.6
POWERPLANT CER
(Thousands of $FY77)

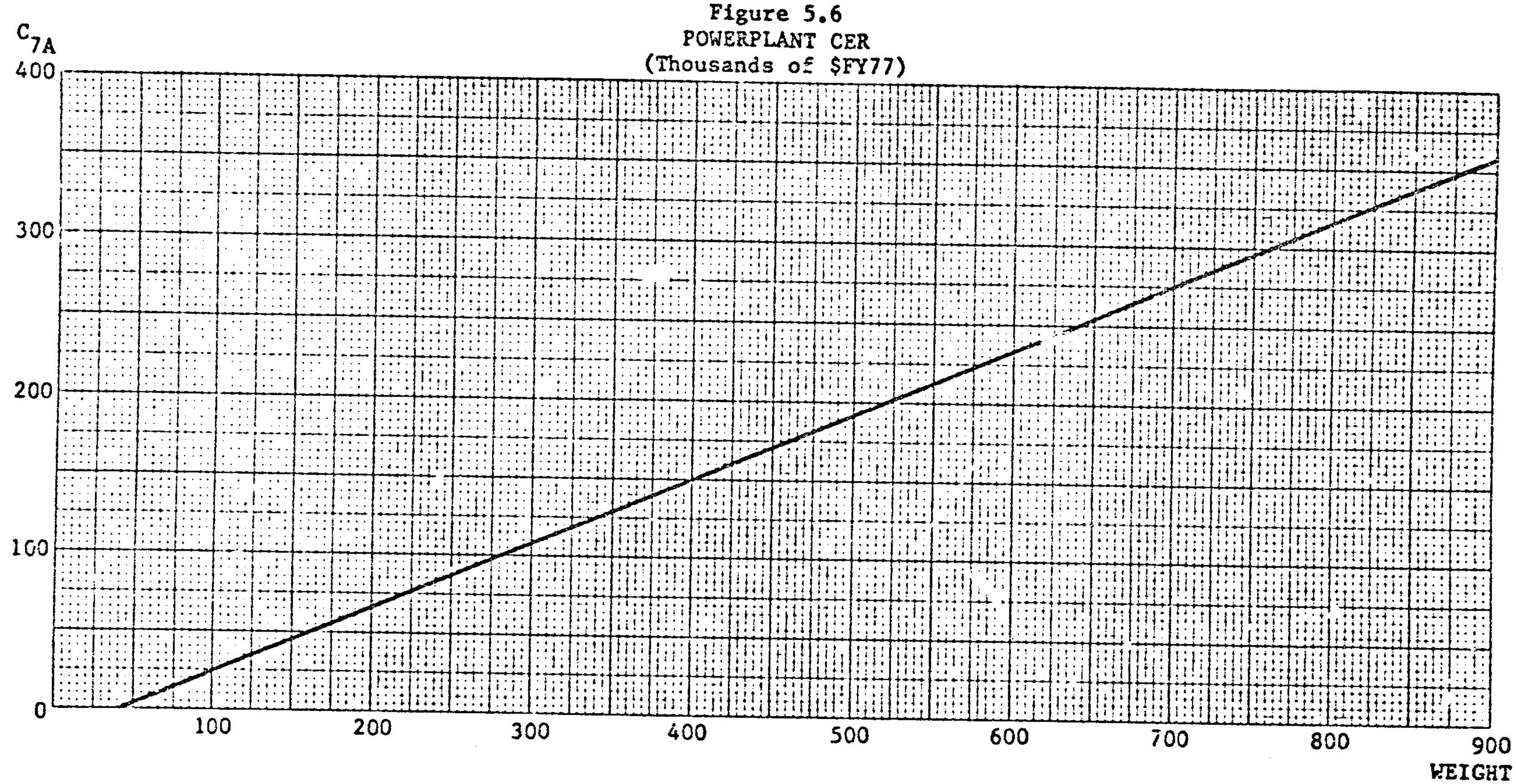


Figure 5.7
DRIVE CER (UNDER 700 POUNDS)
(Thousands of $FY77)

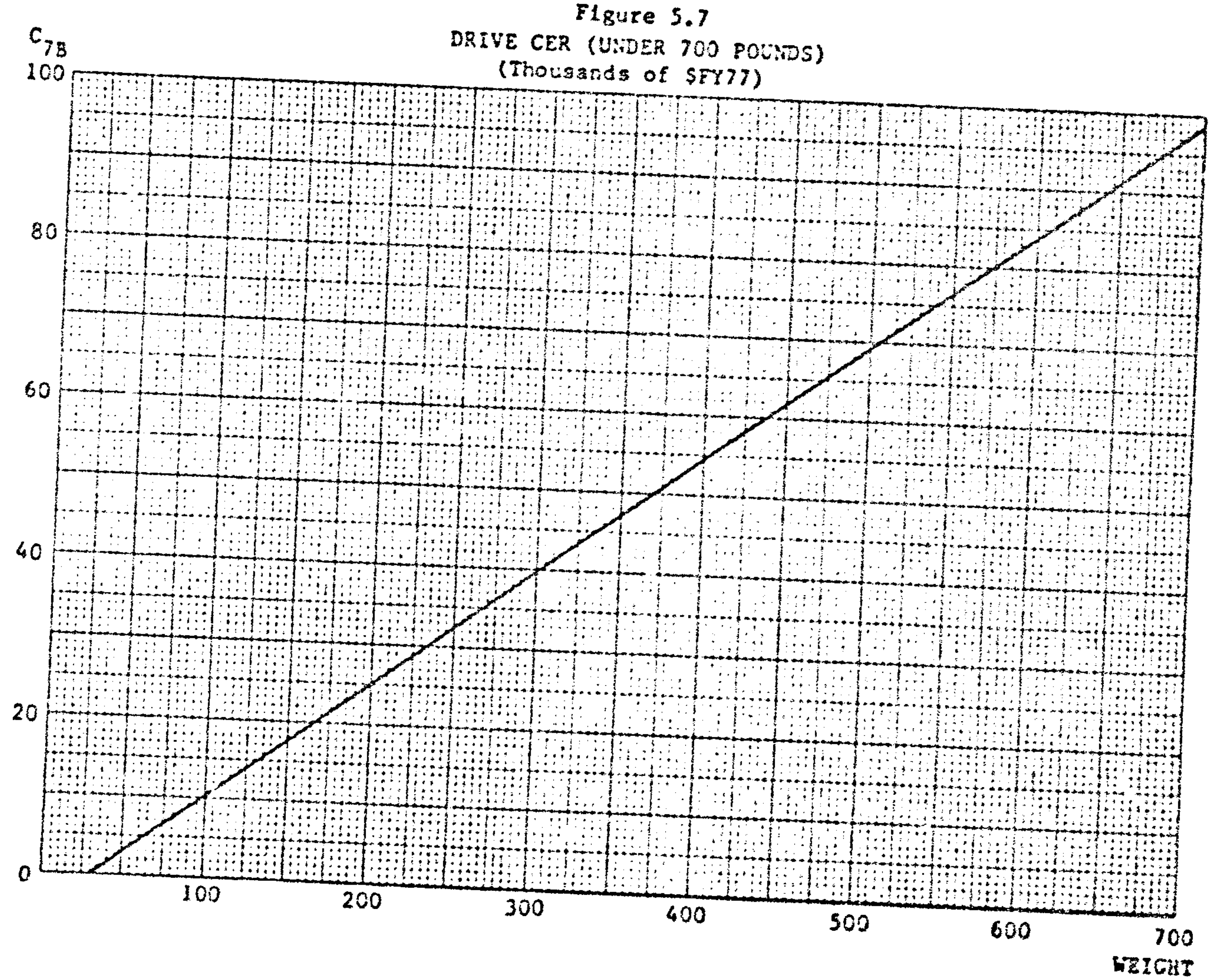


Figure 5.8
DRIVE CER (OVER 1,800 POUNDS)
(Thousands of $FY77)

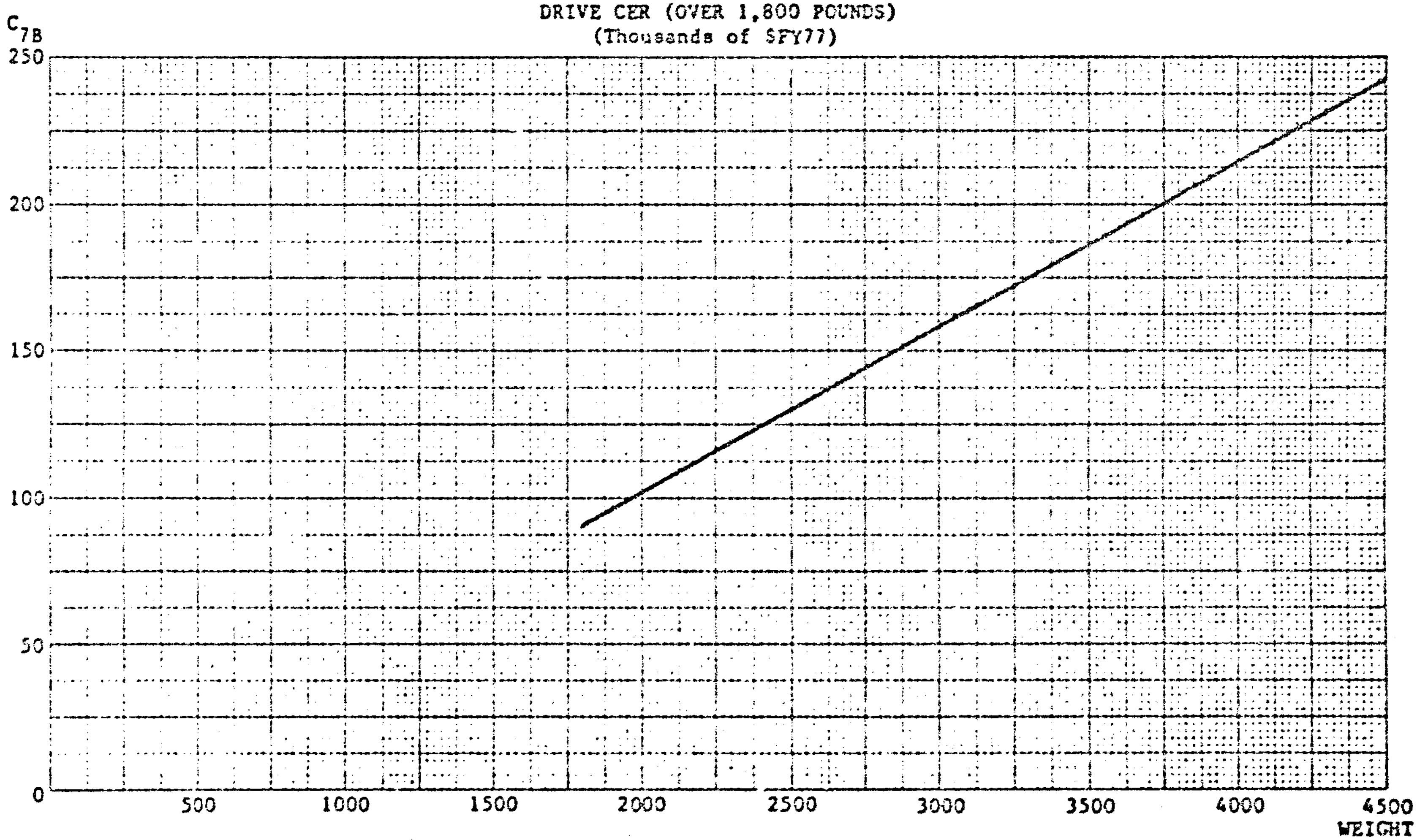


Figure 5.9
DRIVE CER (ALL)
(Thousands of $FY77)

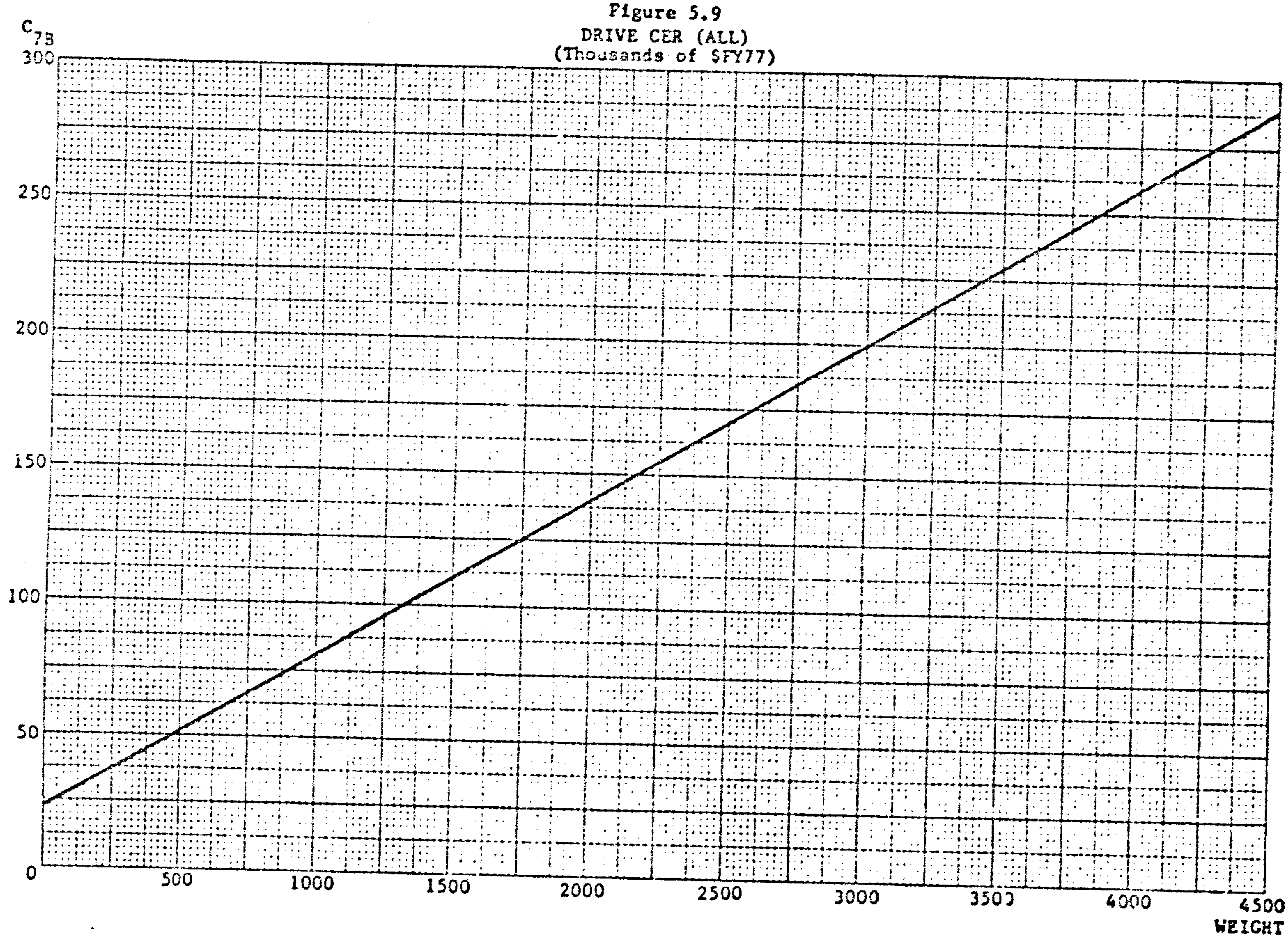


Figure 5.10
FUEL SYSTEM CER
(Thousands of $FY77)

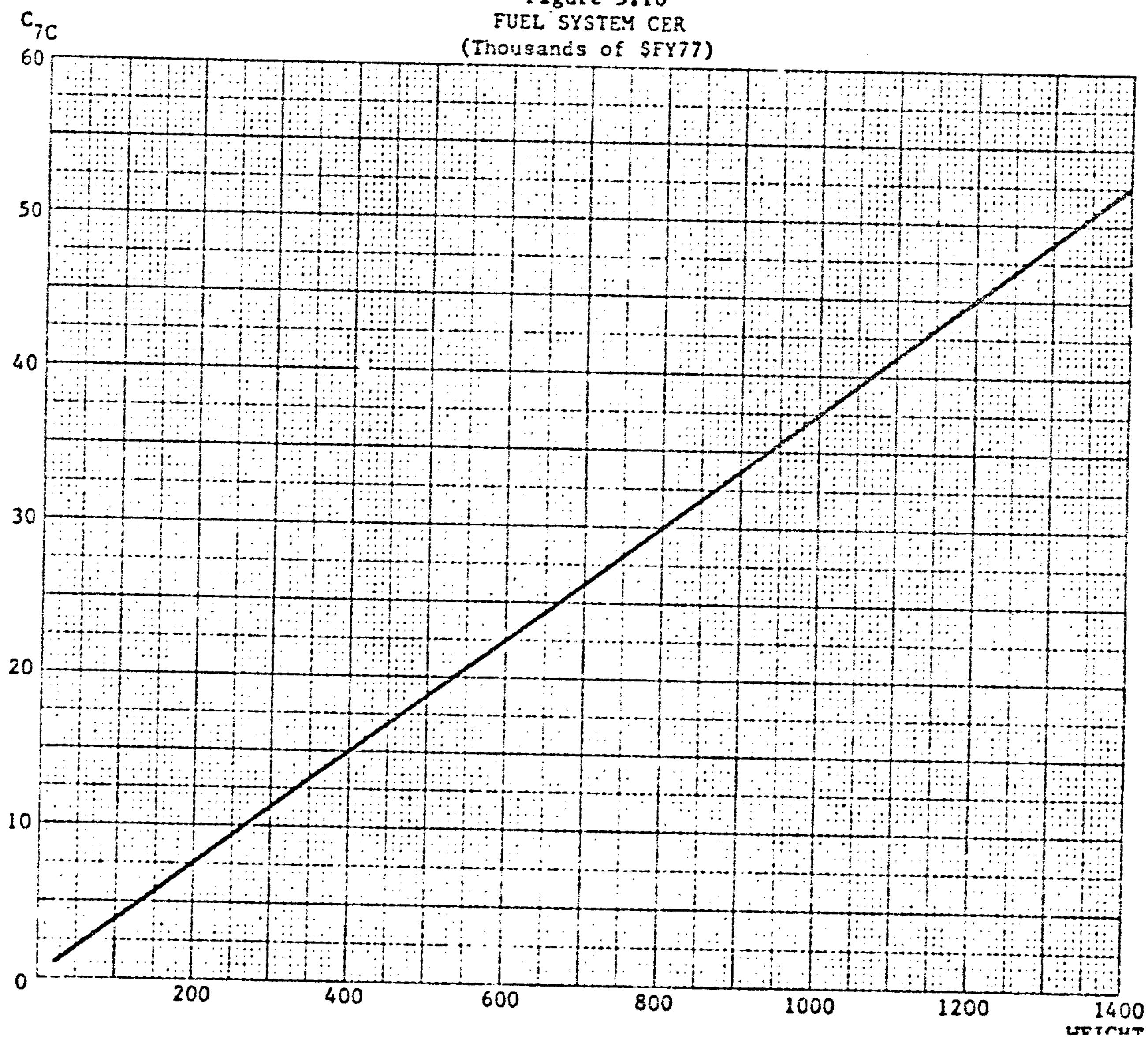
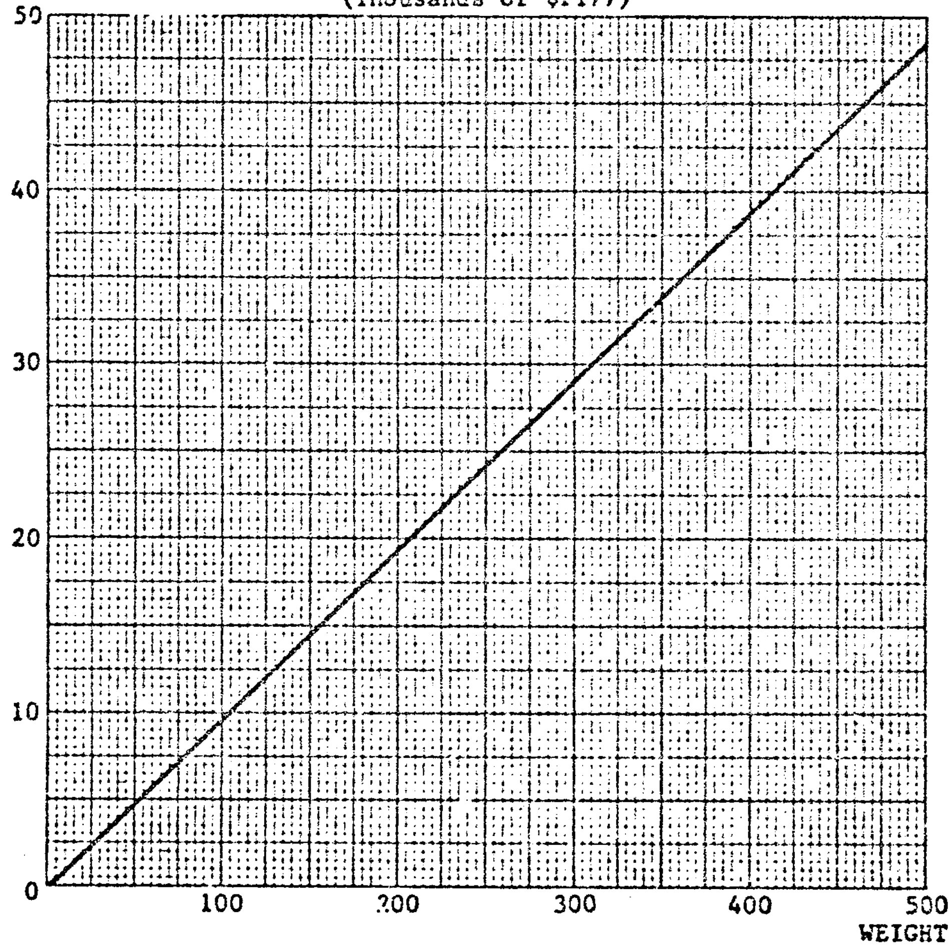


Figure 5.11
OTHER PROPULSION CER
(Thousands of $FY77)



E. FLIGHT CONTROLS SYSTEM

Discussion of Flight Controls System Cost Data and CER Development

The flight controls system CER was developed based on information obtained from a subcontractor interview which was used in conjunction with cost data for transport aircraft flight controls.(1) It was determined that the costs per pound used for cabin controls, plumbing, fluid and supports and miscellaneous hardware in the transport aircraft study were directly applicable to their helicopter counterparts.* The cost drivers in the helicopter flight controls system are the hydraulic and mechanical controls, however.

The hydraulic and mechanical flight controls in helicopters encounter different problems from those of their transport aircraft counterparts. They are much more subject to dust and receive significantly greater vibration. The hydraulic controls present packaging problems because of severe space restrictions. Very complex mechanical controls, including a swash plate and "mixing box," are required because of the rotor. Further, weight is an even greater concern for helicopter flight controls than for their transport aircraft counterparts.

Because of these factors, CAC_{100} costs per pound of $150 to $200 and $75 to $125 were used for hydraulic and mechanical controls, respectively.

The CAC_{100} cost per pound for helicopter flight controls systems is developed in Table 5.1, in accordance with the methodology discussed in Section 3. The following helicopter flight controls CER was developed:

$$C_8 = 156 W_8 Q^{-0.0896}$$

A 94 percent learning curve was assumed.

---

* It was determined that the cost range for plumbing ($5 to $20 per pound) was probably understated because it did not adequately reflect fabrication costs and a higher cost ($20 to $60 per pound) was, therefore, used. No change was made for the costs of the other items.

Table 5.1

FLIGHT CONTROLS SYSTEM
COSTS AND CONFIDENCE VALUES

Major Component or Subassembly	Component % of System Weight	Cost per Pound	Confidence Value
Cabin Controls	9 %	$ 40- 60	2
Plumbing	5	20- 60	6
Fluid	2	0.68	8
Supports and Miscellaneous	13	25- 75	3
Hydraulic Controls	26	150-200	7
Mechanical Controls	45	75-125	4
	100 %	$ 81-126	4.7
		(avg. $104/pound)	

This CER is presented in Figure 5.12. This figure represents the cumulative average cost for 100 units in 1977 dollars and includes only the in-house production and subcontractor costs, as discussed in Section 3.

Perceived Validity of Flight Controls System CER

A confidence value of 4.7 was calculated for the flight controls system CER in Table 5.1, in accordance with the methodology described in Section 3. The major component or subassembly confidence values given to cabin controls, fluid and supports and miscellaneous are identical to those of their transport aircraft counterparts.(1) Plumbing was given a slightly higher confidence value (6 vs. 5). The confidence values assigned to the hydraulic and mechanical controls were, however, significantly lower than those assigned to their transport aircraft counterparts (7 vs. 9.5 and 4 vs. 7.5, respectively) because limited cost data were available and because costs on these items were estimated based on assumptions regarding their relative complexity compared to their transport aircraft counterparts.

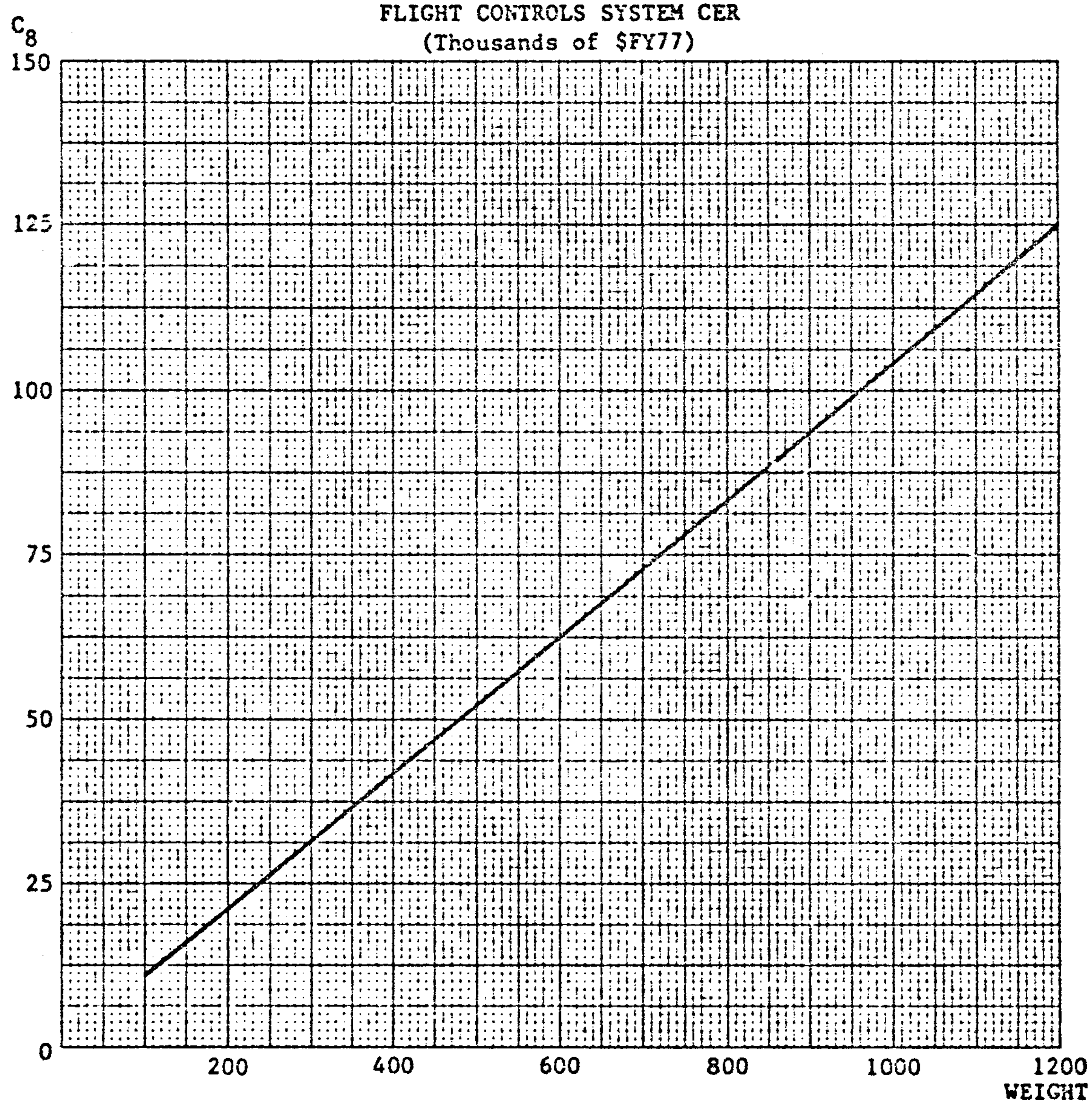
Emerging Technologies

Fly-by-wire has been experimentally implemented on some helicopter designs, including a CH-47. This has been successful but more costly than existing technology. It does, nonetheless, offer greater redundancy with significantly reduced weight. It is expected that, when fly-by-wire controls are implemented on a production model, they will remain more expensive and will also have a shallower learning curve because of the many electronic items included in them which are on the flat part of their own learning curves.

Power-by-wire is another possible new technology which is similar to fly-by-wire except that hydraulic packages including pumps and reservoirs would be located at the actuator.

Fly-by-light is a technology similar to fly-by-wire except that light would be substituted for electricity. This would alleviate potential problems caused by lightning to a fly-by-wire system. It appears to be even further away from implementation than fly-by-wire.

Figure 5.12
FLIGHT CONTROLS SYSTEM CER
(Thousands of $FY77)



F. INTEGRATED PNEUMATIC SYSTEM

Integrated pneumatic system (IPS) is a term often applied to the combined pneumatic, air conditioning, anti-icing and auxiliary power systems. Although these systems are treated separately in Military Standard 1374A (except for the pneumatic system, which is combined with the hydraulic system), the manufacturers and their major subcontractors consider them as part of a single system because of their commonality.

Discussion of IPS Cost Data and CER Development

In the past, pneumatic power has been used only sparingly on helicopters. In fact, for all of the helicopter detail weight statements reviewed, only helicopters with MEWs in excess of 12,000 pounds incorporated auxiliary power or anti-icing systems and no helicopters incorporated pneumatic power systems as such. It is anticipated, however, that pneumatic power will be included on future designs where a heavy lifting capability is required and it has even been suggested as a weight saving alternative for blade cyclic control.

One of the subcontractors who provided the cost data for transport aircraft IPS was contacted regarding helicopter IPS costs. It was suggested that IPS CERs developed for transport aircraft would be appropriate for helicopters. Thus, small transport aircraft CERs(1) were modified by deleting system level assembly and profit and inflating them to reflect $FY77.

The IPS CERs are:

System	Equation
Auxiliary Power	$C_9 = 234W_9\,Q^{-0.0896}$
Pneumatic*	$C_{12} = 137W_{12}Q^{-0.0896}$
Air Conditioning	$C_{16} = 208W_{16}Q^{-0.0896}$
Anti-Icing	$C_{17} = 213W_{17}Q^{-0.0896}$

Learning curves of 94 percent were assumed.

---

* A CER for the pneumatic system is only provided for information, since (as noted) no helicopter studied had a pneumatic system defined as such.

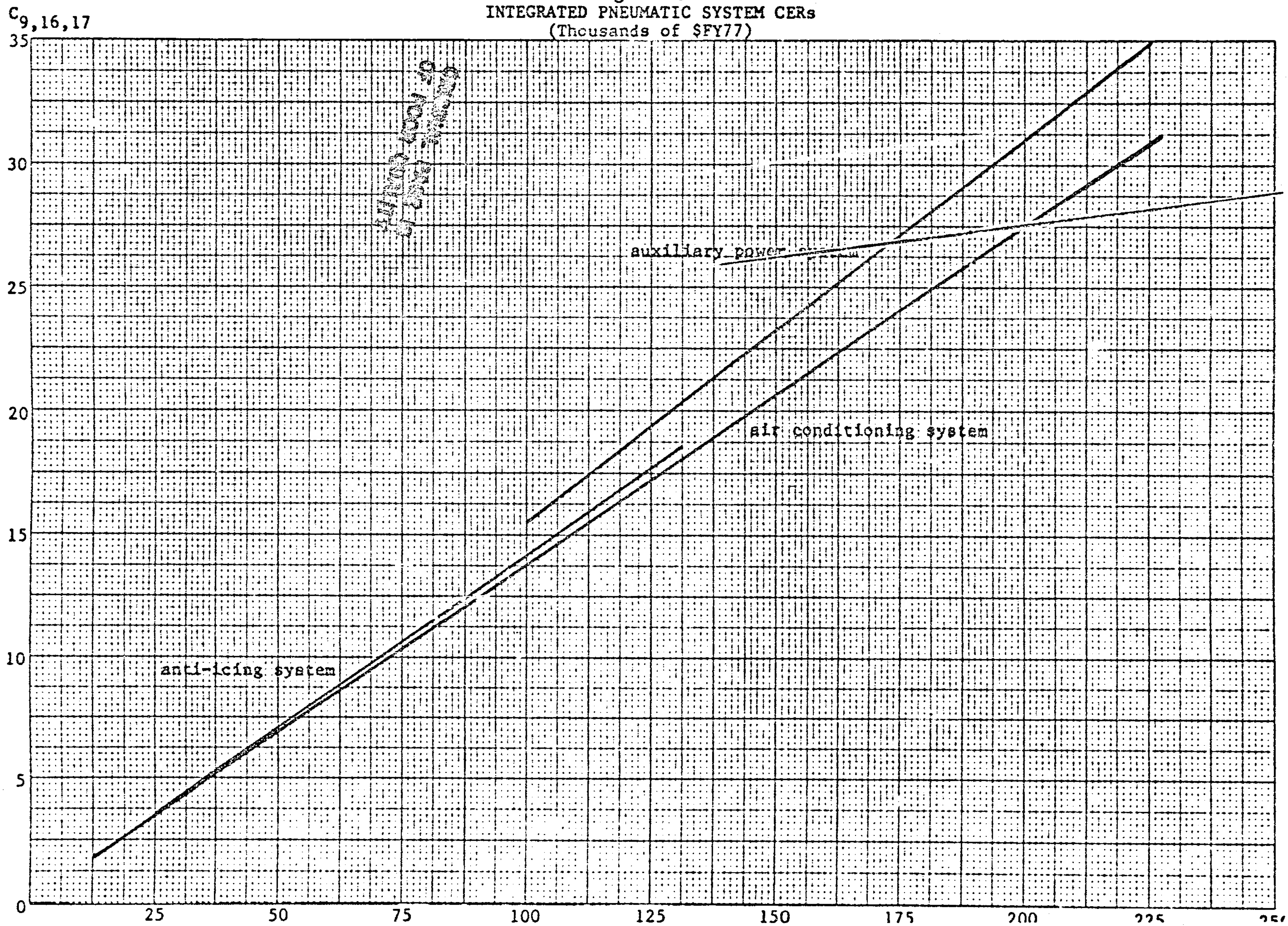
The integrated pneumatic system CERs, except for the pneumatic system, are presented in Figure 5.13. This figure represents the cumulative average cost of 100 units in $FY77 and includes only in-house production and subcontractor costs, as discussed in Section 3.

Perceived Validity of IPS CERs

As noted above, the helicopter IPS CERs are based on a subcontractor statement that the cost of these systems would be essentially the same as that of their small transport aircraft counterparts. Because no specific data for helicopter IPS were obtained and no detailed analyses were performed, relatively low confidence values have been assigned to these systems. Confidence values assigned to the four systems are shown below. Those assigned to their small transport aircraft counterparts are shown in parentheses for comparison.

System	Confidence Value
Auxiliary Power	3.5 (4.5)
Pneumatics	6 (7.8)
Air Conditioning	3 (4.0)
Anti-Icing	6 (8.4)

Figure 5.13
INTEGRATED PNEUMATIC SYSTEM CERs
(Thousands of $FY77)



G. INSTRUMENTS AND AVIONICS SYSTEMS

Discussion of Instrument and Avionics Systems Cost Data and CER Development

Instruments and avionics costs are difficult to estimate for two general reasons:

- Rapidly advancing technology is simultaneously decreasing the weight of existing equipment while bringing state-of-the-art equipment to the market with greatly improved capabilities at a higher unit cost.
- The avionics equipment installed is largely a customer option and may vary greatly on any given helicopter model with its mission, the extent to which the customer wishes to maintain standard equipment within its fleet or other unique user requirements.

As an indication of how much avionics costs can vary, the following ranges of costs per pound for helicopter avionics equipment items were observed:

Item	Range
Gyro compass	$77 - 329
Automatic Direction Finder	97 - 190
High Frequency Radio Set	94 - 372

Costs per pound in excess of $2,000 for some avionic equipment items were observed.

In addition to the above general reasons, there were specific problems with the available cost data which undermined their credibility:

- Quantity data were not available.*
- In several cases, weight and cost data were not available for all avionics equipment installed on a helicopter.

* This may not be a problem because 95 percent learning curve slope is typical for avionics equipment, and, judging from the quantity of helicopters procured, and from the fact that a given item may be found on many helicopter models, the items may have been on the flat part of the curve.

- In several cases, the total avionics equipment weight exceeded that indicated on the weight statement.

Nevertheless, the available cost and weight data included electronic equipment items from 8 different helicopter models, including 14 types. These data were broken into the categories defined above and carefully analyzed to eliminate unexplainable outliers. The average cost per pound for this equipment was about $180, with a standard deviation of about $100. A regression analysis was then performed to develop the following CER:

$$C_{14A} = 13,693 + 110W_{14A}$$

This CER has an r^2 of 0.7621. It is emphasized, however, that the estimate could be from 25 to 200 percent of the actual cost, depending upon the functions required and the equipment selected to perform them. It is noted, however, that, when communications equipment comprises a relatively high proportion of the avionics equipment, the cost will tend toward the lower (say, 70 percent) part of the range.

As mentioned, learning was impossible to determine from the available data; however, it is quite possible that the items represented by this CER are on the flat part of the curve. This CER yields much lower cost estimates than does its transport aircraft counterpart. This is logical, given the less complex nature of helicopter avionics equipment.

Evidence indicated that instrument equipment costs were lower than avionics equipment costs. As a result, a CER which eliminated the constant factor appears to represent the limited data available. It is, simply:

$$C_{10A} = 110W_{10A}$$

Other instrument and avionics items include supports and rack structures, antennae, etc. The CERs for these were developed from those provided for their transport aircraft counterparts[1] by eliminating system level assembly and profit and inflating them to $FY77. These CERs are:

System	Equation
Other Instruments	$C_{10B} = 140W_{10B}Q^{-0.184}$
Other Avionics	$C_{14B} = 140W_{14B}Q^{-0.184}$

A learning curve of 88 percent was incorporated into the equation.

These CERs are presented in Figure 5.14. This figure represents the cumulative average cost of 100 units in 1977 dollars and includes only in-house production and subcontractor costs, as discussed in Section 3.

The instruments and avionics CERs provided above at the subsystem level should be used whenever possible to insure greater accuracy. However, if only total system weight data are available, the following total system CERs were derived for instruments and avionics, respectively:

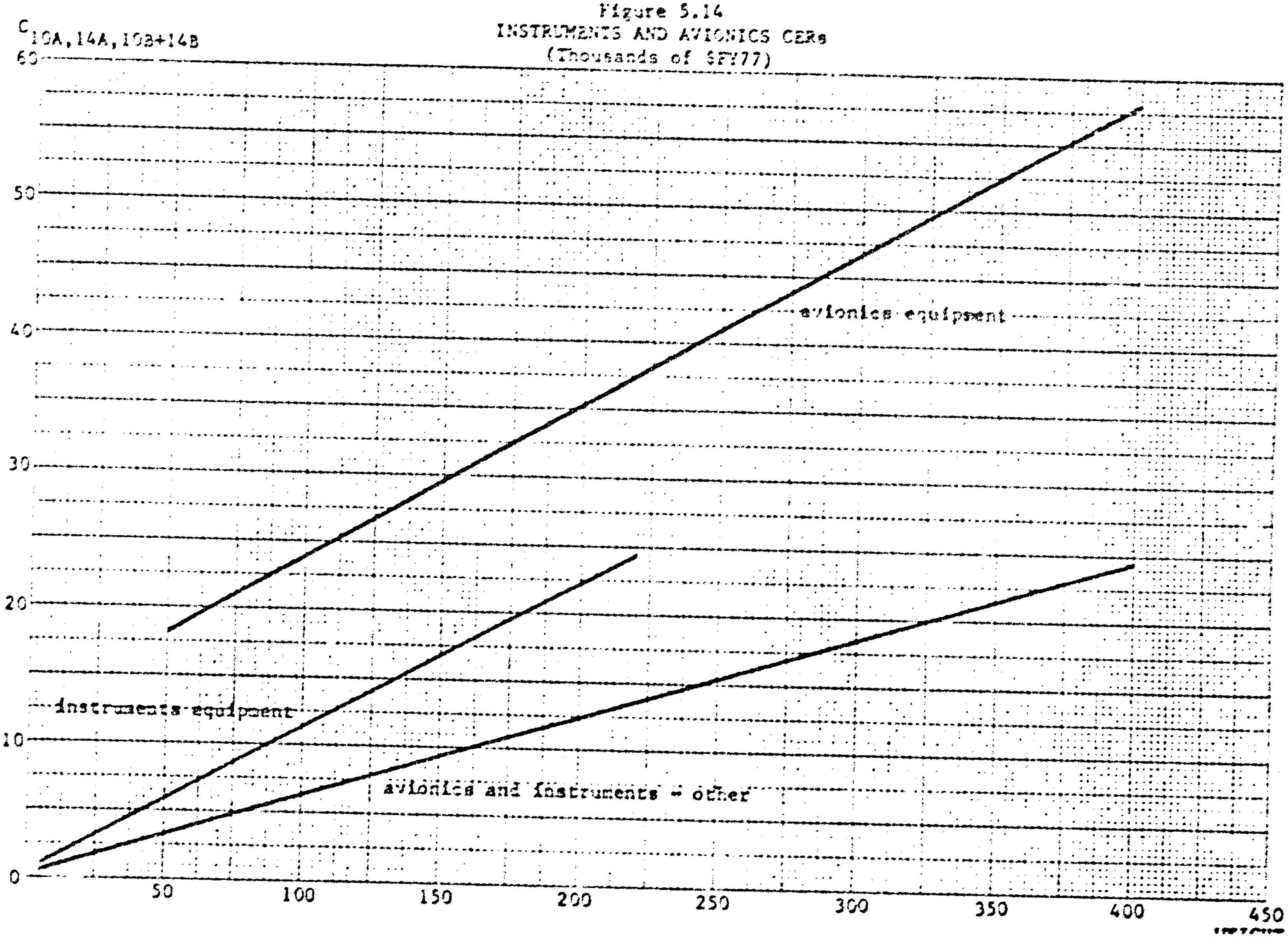
$$C_{10} = 125W_{10}\ Q^{-0.0896}$$

$$C_{14} = 6847 + 125W_{14}\ Q^{-0.0896}$$

Perceived Validity of Instruments and Avionics Systems CERs

As noted, the avionics equipment CER had a correlation coefficient of 0.7621. It was, however, based on less than optimal data. Therefore, a confidence value of 8 was assigned to it in accordance with the criteria provided in Table 3.3. Since the instrument equipment CER was based largely on the avionics equipment CER, a lower confidence value of 5 was assigned to it. A confidence value of 6 was assigned to both other instruments and other avionics. Because of variance in the portion of equipment and other material, lower confidence values were assigned to the total system CERs: 4 for instruments and 6 for avionics.

Figure 5.14
INSTRUMENTS AND AVIONICS CERs
(Thousands of $FY77)



H. HYDRAULIC SYSTEM

Discussion of Hydraulic System Cost Data and CER Development

The hydraulic system CER was developed based on subcontractor-provided information as well as on assumptions made regarding the analogy of certain components to their transport aircraft counterparts.[1]

Hydraulic pumps are the key cost driver in the hydraulic system. One pump is provided per engine and, since it is usually limited to providing power only for the hydraulic flight controls, its output is smaller than its transport aircraft counterpart (20 to 50 HP, compared to 100 HP or more). There is greater concern for weight on helicopters and, as a result, their hydraulic pumps are lighter on a per horsepower basis than their transport aircraft counterparts. Helicopter hydraulic pumps, therefore, cost about \$100 to \$200 per pound, compared to \$65 to \$75 per pound for their transport aircraft counterparts. In certain installations, hydraulic pump/starters are used and once the engine is started by the unit it then functions as a pump. This provides self-sufficiency in the field as ground support equipment is not required. The total cost of these pump/starters is between \$3,500 and \$5,000.

The cost of reservoirs, accumulators, filters, regulators, valves and manifolds is higher for helicopters than for transport aircraft, primarily because of the increased design and manufacturing difficulty incurred by making them smaller. Collectively, these items cost between \$75 and \$125 per pound.

The cost per pound of the remaining items (plumbing, fluid, and supports and miscellaneous) is the same as for their equivalents in the flight control system, which was discussed above.

The CAC_{100} cost per pound for helicopter hydraulic systems is developed in Table 5.2, in accordance with the methodology discussed in Section 3. The following hydraulic system CER was calculated:

$$C_{11} = 91 W_{11} Q^{-0.0896}$$

A 94 percent learning curve was assumed.

Table 5.2

HYDRAULIC SYSTEM
COSTS AND CONFIDENCE VALUES

Major Component or Subassembly	Component % of System Weight	Cost per Pound	Confidence Value
Hydraulic Pumps	17 %	$100-200	9
Reservoirs, Accumulators, Filters, Regulators, Valves and Manifolds	18	75-125	5
Plumbing	27	20- 60	6
Fluid	26	0.68	8
Supports and Miscellaneous	12	25- 75	3
	100 %	$ 39- 82	6.5
		(avg. $60/pound)	

The CER is presented in Figure 5.15. This figure represents the cumulative average cost for 100 units in 1977 dollars and includes only in-house production and subcontractor costs as discussed in Section 3.

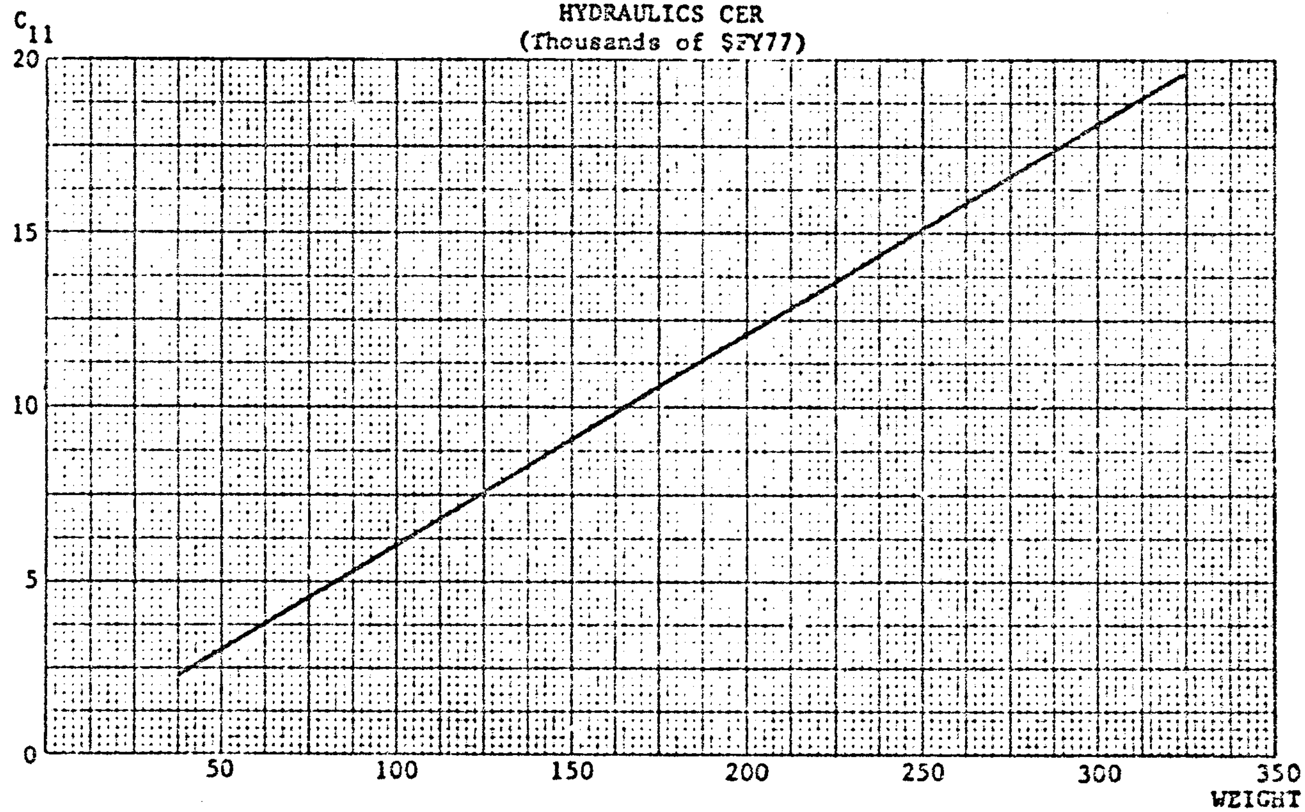
Perceived Validity of Hydraulic System CER

A confidence value of 6.5 is developed in Table 5.2 for the hydraulic system CER, in accordance with the methodology indicated in Section 3. Component or major assembly confidence values for plumbing, fluid and supports and miscellaneous are the same as for their flight control system equivalents which were discussed above. A relatively high confidence value (9) was assigned to hydraulic pumps because of the detailed discussion provided by a subcontractor. On the other hand, the aggregated cost per pound estimate for reservoirs, accumulators, filters, regulators, valves and manifolds was assigned a relatively low confidence value (5) because it was based on assumptions regarding analogies and detailed information was not available.

Emerging Technologies

Power-by-wire, which was discussed briefly with the flight control system, would affect the cost of the hydraulic system. Since hydraulic system components would be colocated with the hydraulic flight control actuators, plumbing would be eliminated, even though additional pumps would be required. This implies a significantly increased hydraulic system cost per pound.

Figure 5.15
HYDRAULICS CER
(Thousands of $FY77)



I. ELECTRICAL SYSTEM

Discussion of Electrical System Cost Data and CER Development

Very detailed cost data were obtained and reported for transport aircraft electical system components.[1] The subcontractors who provided these data were contacted and questioned regarding their applicability to helicopters. They indicated that the electrical system major components and subassemblies for transport aircraft were identical to those for helicopters, with the following key exceptions:

- Since helicopter drives operate at a constant speed, constant speed drives (CSDs) are not required. This results in a significant cost savings.
- Helicopters use less sophisticated electrical controls than do transport aircraft; these items, therefore, cost only about two-thirds as much.

By applying these considerations to the detailed transport aircraft electrical system cost data,[1] a total CAC_{100} for helicopter electrical systems of about \$74 per pound was estimated. The following electrical system CER was calculated:

$$C_{13} = 143W_{13}\ Q^{-0.0895}$$

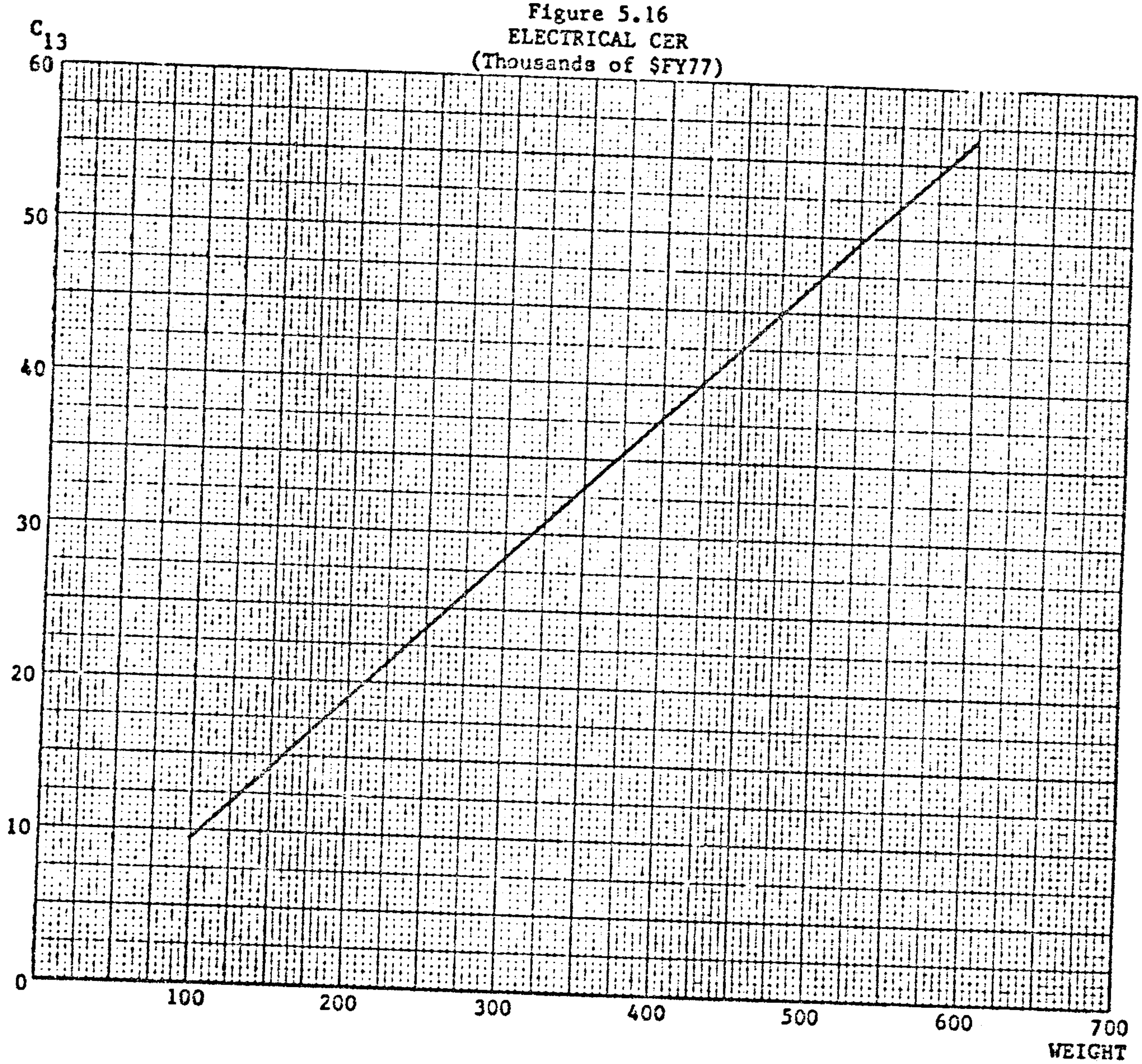
A 94 percent learning curve was assumed. A cost of about \$86 per pound was estimated for an all DC helicopter. Thus, an upward adjustment of the CER would probably be appropriate if an all DC system was contemplated.

The CER for a typical AC/DC electrical system is presented in Figure 5.16. This figure represents the cumulative average cost of 100 units in 1977 dollars and includes only in-house production and subcontractor costs, as discussed in Section 3.

Perceived Validity of Electrical System CER

Because good data were acquired for transport aircraft electrical systems[2] and because the differences between them and their helicopter

Figure 5.16
ELECTRICAL CER
(Thousands of $FY77)



counterparts were thoroughly understood, the confidence values assigned to transport aircraft electrical systems were used for helicopter electrical systems after modifications to reflect the design differences mentioned above. A confidence value of 8 was the result.

J. FURNISHINGS AND EQUIPMENT SYSTEM

Discussion of Furnishings and Equipment System Cost Data and CER Development

In developing furnishings and equipment CERs for transport aircraft[1] it was necessary to contact many subcontractors in order to represent the wide range of items included in this system adequately. Once these diverse cost data were collected, it was necessary to aggregate these items into categories with other similar, related items. The relative mix of these categories in the complete system caused the estimated cost per pound of the total system to vary by nearly 20 percent from small to wide body transport aircraft ($40 to $57 per pound).

A careful analysis of detail weight statements for furnishings and equipment included on five diverse military helicopters indicated that subcategories similar to those developed for transport aircraft could be established. Further, there was no reason to believe that the cost data used to develop CERs for transport aircraft furnishings and equipment would not be appropriate for application to their helicopter counterparts. Thus, the CAC_{100} cost per pound for helicopter furnishings and equipment systems is developed in Table 5.3, in accordance with the methodology discussed in Section 3. The following furnishings and equipment CER was calculated:

$$C_{15} = 69W_{15}\, Q^{-0.0896}$$

A 94 percent learning curve was assumed.

It is cautioned that, because of the unavailability of detail weight breakdowns for commercial helicopters, this CER represents the mix of components found on military helicopters only. Although it is expected that the same furnishings and equipment categories would be found on commercial helicopters, it is probable that their mix would be different and another (probably higher) CER should be developed and used for them.

The CER is presented in Figure 5.17. This figure represents the cumulative average cost of 100 units in 1977 dollars and includes only in-house production and subcontractor costs, as discussed in Section 3.

Table 5.3

FURNISHINGS AND EQUIPMENT SYSTEM
COSTS AND CONFIDENCE VALUES

Major Component or Subassembly	Component % of System Weight	Cost Per Pound	Confidence Value
Seats and Chairs	56 %	$ 30– 36	8
Instruments Panel, Console Glare Shield, Wipers	11	42– 91	2
Insulation	15	28– 60	3
Fire Detection	2	150	3
Oxygen	2	51	8
Cargo Handling	5	60– 80	2
Other Emergency Equipment	9	42– 91	2
	100 %	$ 36– 55	5.7
		(avg. $46/pound)	

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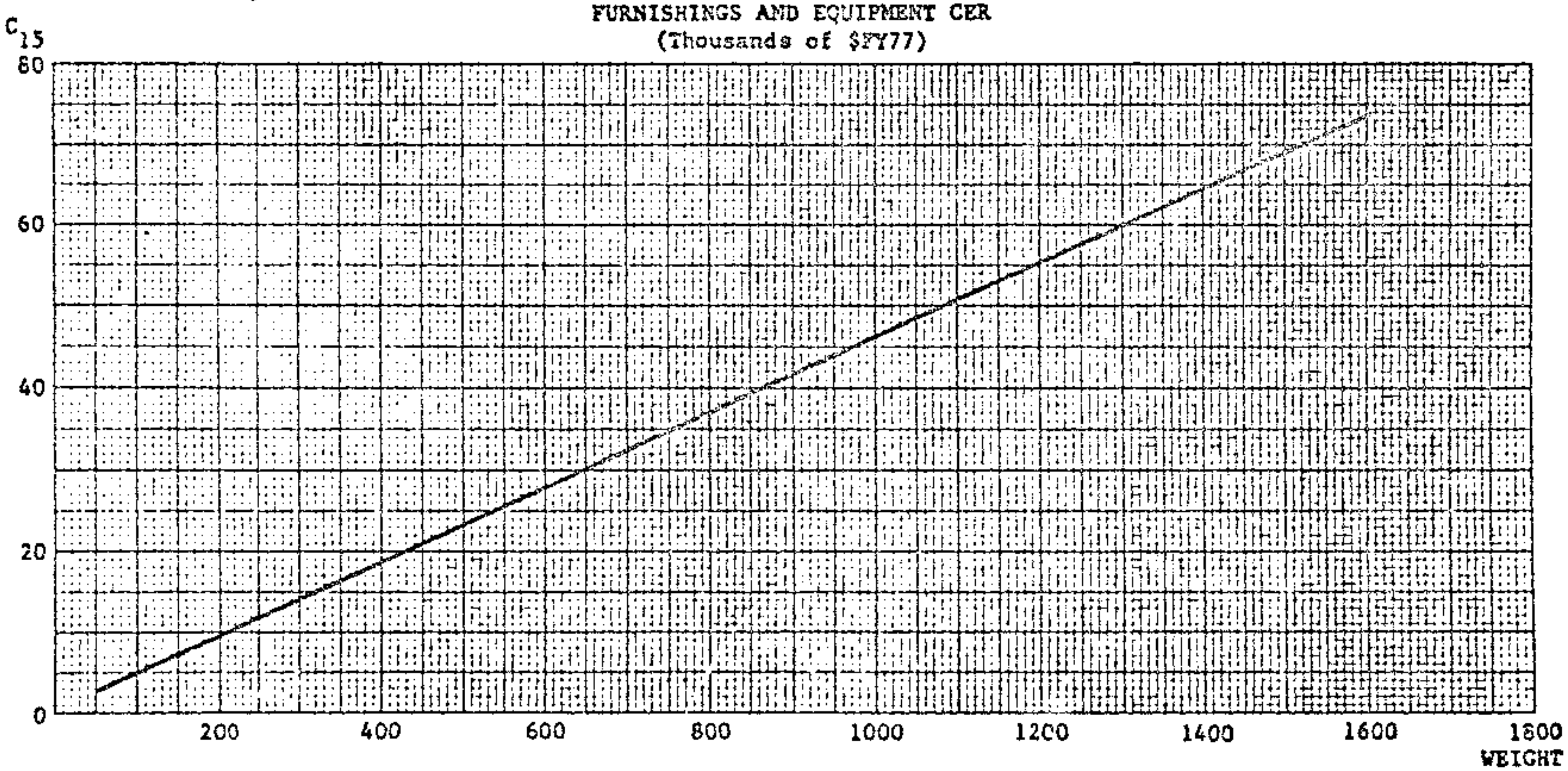
Figure 5.17
FURNISHINGS AND EQUIPMENT CER
(Thousands of $FY77)



Perceived Validity of Furnishings and Equipment System CER

A confidence value of 5.7 is developed in Table 5.3 for the furnishings and equipment CER, in accordance with the methodology discussed in Section 3. Although the confidence values assigned to most of the individual components or major subassemblies were quite low (2 or 3), the overall confidence value is considerably higher because of the good cost data available for seating and the high proportion of seating (56 percent) in the system. It is again noted that both the CER and the confidence value are applicable to furnishings and equipment systems for military helicopters and that these could change significantly when applied to commercial helicopters.

K. LOAD AND HANDLING SYSTEM

Discussion of Load and Handling System Cost Data and CER Development

The load and handling system represents an insignificant cost in the production of a helicopter (less than one percent). As it is such a minor item, no independent research was devoted to this system. Because of its similarity to and location in the body, it was assumed to have the same cost per pound as the body.

The CER is:

$$C_{18} = \frac{W_{18}}{W_4} C_4$$

Perceived Validity of Load and Handling CER

Because no cost data were collected for this system and but minimal analysis was performed, a very low confidence value (1) was assigned to the load and handling system CER, in accordance with the criteria in Table 3.3.

I. IN-HOUSE ASSEMBLY

In-house assembly includes all labor by the helicopter manufacturer required to integrate major components and subassemblies into a finished helicopter. The following cost elements are included: major and minor assembly, installation and checkout, and quality control. A description of all recurring production cost elements is included in Appendix A.

While some of this cost could be attributed to individual systems, the proportion would undoubtedly vary significantly among them. For example, the in-house assembly associated with the body would be much greater than for the auxiliary power system, which could simply be bolted into place. Also, much of this cost is at the total helicopter level and could not reasonably be allocated to the individual systems. It is therefore presented as a separate CER.

Discussion of In-House Assembly Cost Data and CER Development

Data were not available for in-house assembly costs per se and, as a result, they were estimated based on total airframe cost data which were available.[2] It was assumed that the total specified cost represented:

- All in-house production and subcontractor costs except those associated with government furnished equipment (wheels, breaks and tires, bare engines, instruments and avionics equipment);
- All in-house assembly costs;
- Profit was not included.

Fourteen helicopter models were identified for which both detailed weight and cost data were available. Problems with some of the cost data (such as the inclusion of non-recurring costs) reduced this sample to nine, which represented helicopters with MEWs from about 2,000 to over 20,000 pounds. The following methodology was followed in estimating in-house production costs:

- Rolling assembly, bare engine, instrument and avionics weights were omitted from the data.

- The system level CERs were applied to all remaining actual weights.*
- The calculated airframe unit weights frequently disagreed slightly (say, ±5 percent) with those indicated in the source.[2]** Thus, the cost was prorated and adjusted accordingly. For example, if the total cost estimate was based on a total weight of 950 pounds and the comparable reported weight was 1,000 pounds, the estimate was adjusted upward by 5 percent.
- The source cost data were adjusted to CAC_{100} in \$FY77 for comparability.
- The actual total cost was divided by the estimated cost to determine a factor for in-house assembly.

The two tandem helicopters included in the sample were observed to have significantly higher in-house assembly costs than the others.*** In-house assembly is, therefore, estimated to represent 46 percent of total recurring production cost for those items which comprise airframe unit weight for single helicopters and 64 percent for tandems at 100 units. In-house assembly was shown to represent about 33 percent of the recurring production cost on transport aircraft. Thus, helicopters are shown to be somewhat more expensive to assembly on a per pound basis than are transport aircraft, which is not surprising, considering their relatively light weight and comparable complexity.

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* It is, of course, possible that errors could occur here. Still, the confidence levels indicated for these CERs was such that it was assumed that any error resulting from them for a particular helicopter would be small and randomly positive or negative.

** When source weights varied by production lot, an average weight was used.

*** It is quite possible that the significantly higher in-house assembly factor calculated for tandem helicopters is in fact a proxy for other factors including, for example, more complex designs or technology, higher costs experienced for a factor of production, or even a less efficient operation. Data were not available which would enable such a determination to be made.

The following CERs were developed for in-house assembly. As indicated, they are a function of all items typically provided by the manufacturer. Attempts were made to include all systems in the equation, however, the cost variance for engines, instruments and avionics was too great to enable this to be done. The learning curve slope included in the in-house assembly equation is relatively steep because of the large portion of hand labor involved.

Equation	Notes
$C_{19} = 5.325\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right] Q^{-0.3959}$	Single: $j = \{5C, 7A, 10, 14\}$
$C_{19} = 10.775\left[\sum_{i=1}^{18} C_i - \sum_j C_j\right] Q^{-0.3959}$	Tandem: $j = \{5C, 7A, 10, 14\}$

Perceived Validity of In-House Assembly CER

Confidence values of 8 and 6 are assigned to the in-house assembly CERs for single and tandem helicopters, respectively, as more data were available for single helicopters and the standard deviation for them was relatively small (±15 percent).

APPENDIX A

DESCRIPTION OF RECURRING PRODUCTION COST ELEMENTS*

IN-HOUSE PRODUCTION includes all labor and raw material related to the production of major components and subassemblies by the helicopter manufacturer. It includes the following cost elements which are described below: fabrication, sustaining engineering and sustaining tooling labor, and raw material.

Fabrication labor performs operations in the manufacturing of detailed parts from raw material and includes cutting, molding, forming, stamping, stretching, machining, heat treating, anodizing, plating, etching, and deburring. It also includes shop coordination, as well as material expediting.

Sustaining engineering labor includes technical staff support, customer engineering and product development engineering labor.

Sustaining tooling labor is expended for the modification and repair of jigs, dies, fixtures, molds, patterns, and other manufacturing aids.

Raw material includes all raw material, such as sheets, bars, and tubes, as well as castings, forgings, and extrusions.

SUBCONTRACTOR includes all major components and subassemblies which are not produced by the helicopter manufacturer. Two cost elements are included: outside production and purchased equipment.

Outside production typically includes major subcontracted items, such as the alighting gear.

Purchased equipment typically includes flight controls, hydraulics (pumps, manifolds, reservoirs, filters, plumbing, valves), electrical (generators, battery, wire, power distribution and control equipment, and lighting), air conditioning (environmental control systems, valves, controls), anti-icing (ducts, electrical), auxiliary power unit,

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* The terminology and grouping of elements vary for different manufacturers.

furnishings and equipment, instruments (flight and navigation systems) and avionics (communication, flight and navigation).

IN-HOUSE ASSEMBLY includes all labor provided by the helicopter manufacturer which is required in order to integrate major components and subassemblies into a finished helicopter. The following cost elements are included: quality control, minor assembly and major assembly.

Quality control labor is concerned primarily with inspection of production and tooling hardware, and with preparation and verification of tests and associated paperwork. Inspection of subcontractor supplied items, both in plant and out of plant, is considered to be an overhead cost.

Minor assembly labor includes those operations which contribute to the manufacturing of an end item consisting of two or more fabricated parts and/or the joining of two or more assembled parts into a major component. This may be accomplished by welding, riveting, soldering, bolting or other fastening methods.

Major assembly labor is broken into three subcategories:

1. Sectional assembly labor includes the effort which produces assemblies which are manufactured and controlled to a unique configuration for a specific helicopter. It includes both "non-position" and "fixed position" stages of the airframe construction. The "non-position" operations can be set up in any factory location where space is available and usually result in subassemblies which will be used in the "fixed positions." The "fixed positions" in the factory area can result in a completed structural subsection or a whole section.

2. Installation and checkout labor operations are performed in installing non-structural equipment and systems in an air vehicle or a section of an air vehicle. Operational and air-worthiness checks of both equipment and airframe structure are also included as is the installation and checkout of all electronics, avionics, electrical systems and wiring.

3. Miscellaneous labor consists of operations such as metal bond testing, cleaning, sealing, and painting.

APPENDIX B

SUMMARY OF SYSTEMS DESCRIPTIONS

1. WING SYSTEM

Helicopters typically do not utilize wings, although some more recent designs have incorporated small wing stubs to improve aerodynamic characteristics or to carry military stores. Unlike the wings on fixed wing aircraft, helicopter wings generally include only a simple box structure and do not normally have control surfaces. Therefore, they do not have to accommodate flight controls, hydraulic items or fuel systems. They may serve as fairings or wheel wells for retracting landing gear.

2. ROTOR SYSTEM

The rotor system consists of the blade assembly and the hub and hinge assembly. The blade assembly includes the interspace structure, leading and trailing edges, tips (if not integral), balance weights, and mounting hardware and blade foldings. The hub and hinge assembly includes the yoke, universal joints, shafting between the rotor system and the drive box, spacers and bushings, lubrication system, fittings, pins, drag brace, retention strap assembly, and fasteners and miscellaneous hardware.

3. TAIL SYSTEM

A tail system may not be present on all helicopters, since tandem designs do not necessarily require a tail. The usual tail system includes all the aerodynamic surfaces and the mounts for the tail rotor. The helicopter tail is a simple structure similar to the wing structure in that control surfaces are not usually incorporated. The tail rotor and the main rotor are defined similarly.

4. BODY SYSTEM

The body system consists of the fuselage shell structure, door and window frames, doors, windows, floors, bulkheads, cockpit windshield, and radome. Door actuation mechanisms, airstairs (when installed) and loading ramps are also included.

5. ALIGHTING GEAR SYSTEM

Helicopters have two general types of alighting gears. Smaller helicopters (under about 3,000 pounds MEW) usually have skids which are fixed runners and which support the airframe on landing. Larger helicopters generally have fixed wheel-type alighting gears to enable them to be towed on the ground and to take off non-vertically. This system includes landing gear structure, which is made up of struts, side and drag braces, trunnions and attachment fittings. The alighting gear controls include components for braking, steering and retraction (on a few newer models). They also include lines from the cockpit controls to the landing gears. The rolling assembly includes wheels, brakes and tires.

6. NACELLE SYSTEM

The nacelle system includes the engine mount, firewall and cowl structure, engine air inlet, oil cooler scoop and miscellaneous installation hardware.

7. PROPULSION SYSTEM

The propulsion system includes three main subsystems: the powerplant, the drive, and the fuel system. The powerplant subsystem includes the dry engine, residual fluids and installation hardware as well as related components: starter, air inductor, exhaust and cooling items, lubrication systems and the engine controls. The drive subsystem includes the gear speed reducers, transmission drive, rotor brake and shaft, and lube system. The fuel subsystem includes the fuel fill and drain system, fuel distribution system, fuel vent plumbing and fuel tanks.

8. FLIGHT CONTROLS SYSTEM

The helicopter flight controls system includes: cabin controls (cyclic control column, collective pitch levers and rudder or tail rotor pedal); mechanical operating mechanism (swash plate, stabilizing bar, linkages, bearings and levers, bellcranks); hydraulic controls; fluid; and miscellaneous hardware.

9. AUXILIARY POWER SYSTEM

The auxiliary power system supplies all power for ground operations in lieu of ground support equipment. These operations include: cabin ground air conditioning, engine starting, and driving a generator for electric power.

10. INSTRUMENTS SYSTEM

Instruments perform basic monitoring and warning functions associated with the flight of the helicopter: electrical, hydraulic and pneumatic systems operation, engine operation and fuel quantity. The instruments system includes cockpit indicators and warning lights, transducers, signal inputs, circuitry, and the monitoring devices.

11. HYDRAULIC SYSTEM

The hydraulic system on helicopters is required primarily to provide hydraulic power to the hydraulic flight controls. In a few cases, hydraulic power is also used for landing gear retraction and to power cargo handling accessories. The hydraulic system includes: pumps, reservoirs, accumulators, filters, regulators, valves, manifolds, plumbing, fluid, and supports and mounting hardware.

12. PNEUMATIC SYSTEM

Curiously, none of the helicopter weight statements examined indicated the existence of a pneumatic system. Thus, the following description is for fixed wing aircraft but should be applicable to helicopter designs which might incorporate a pneumatic system.

The pneumatic system includes all heat exchangers and ducting, which carries pressurized ari from each of the main engines and from the auxiliary power unit (APU). The pneumatic system provides compressed air for cabin pressurization, air conditioning and ventilation, engine starting, ice prevention and turbine-driven supplementary or emergency hydraulic power.

13. ELECTRICAL SYSTEM

The electrical system supplies power to a variety of helicopter operating components, including, among others: lights, avionics, instruments, passenger and cargo doors, cargo hoist, and environmental control system.

The electrical system consists of the AC power system, the DC power system and the lighting system. The AC system includes power generating equipment, while the DC power system includes converters and batteries, and both include the necessary controls, wiring, cables, fittings and supports to distribute the electrical power from the power source to the electrical power center.

The lighting system includes all interior and exterior lights, together with the switches, associated circuitry from the electric power center, and support hardware.

The wiring and circuitry leading from the electric power center to the various components which use electricity are included with the respective systems.

14. AVIONICS SYSTEM

The avionics system is separated into four subsystems. They are described in the following paragraphs.

Integrated Flight Guidance and Controls Subsystem

The integrated flight guidance and controls subsystem includes the autopilot unit, the flight director unit, the gyrocompass unit, the attitude and heading reference unit, and the inertial navigation unit. These units are interdependent and may be either separate, interconnected units or one, integrated functional unit. All indicators, servomechanisms, and associated circuitry, supports and attachments related to the integrated flight guidance and controls subsystem are also included. Although usually colocated with this subsystem, the auto-throttle/thrust management unit is part of the propulsion system because it functions to control the engine.

Communication Subsystem

The communication subsystem is separated into internal and external units. The internal communication unit includes the interphone system, the public address system, and the multiplex (MUX) system. The external communication unit includes the transceiver equipment which is used for aircraft-to-aircraft or aircraft-to-ground communications.

Navigation Subsystem

The navigation subsystem includes all radar equipment, the automatic direction finding (ADF) unit, the distance measuring equipment (DME) unit, the doppler unit, the navigation computer units, the station-keeping unit, the tactical air navigation (TACAN) unit, the variable omnirange (VOR) unit, the marker beacon unit, the instrument landing system (ILS), the collision avoidance unit (CAS), the airport traffic control (ATC) unit, the radio altimeter unit, the glide slope indicator, and the radar beacon unit. All of the navigation units, indicators, antennae, associated circuitry and antenna coaxial cable, and the units' supports and attachements related to the navigation subsystem are included.

Miscellaneous Equipment Subsystem

The miscellaneous equipment subsystem includes the flight, voice and crash recorder unit, the aircraft integrated data (AID)/malfunction detection analysis and recording (MADAR) unit, the weight and balance unit (if installed), and the equipment rack structure and mounting hardware and circuitry.

15. FURNISHINGS AND EQUIPMENT SYSTEM

Furnishings and equipment include a variety of items in the cockpit and the passenger and/or cargo compartment. In the cockpit, this category includes all instrument and console panels, seats, insulation, lining, crew oxygen system, and cockpit door and partitions.

In the passenger and/or cargo compartment, this category includes seats, floor covering, insulation, side panels, ceiling structure, hatrack or baggage containers, and passenger comfort items such as galley or lavatory installations.

Miscellaneous items include the engine and cabin fire extinguisher systems, fire warning system, exterior finish, and emergency equipment (i.e., first aid kit and fire ax). Cargo loading equipment is also a part of this system.

16. AIR CONDITIONING SYSTEM

The air conditioning system, in addition to supplying conditioned air to the cabin, heats the cargo compartment and supplies conditioned air for avionic and electrical load center cooling.

17. ANTI-ICING SYSTEM

Anti-icing functions can be performed either by hot bleed air or by electrical heat. Bleed air systems include all ducting from the main pneumatic source and inner skins, which form the hot air cavities. Electrical systems include the electrical blankets fastened to the outer surfaces of critical items, plus all wiring and controls.

18. LOAD AND HANDLING SYSTEM

The load and handling system consists of loading and handling gear, including provisions for jacking, hoisting and mooring, and ballast.

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